VOLUME, 19 JANUARY, 1931 NUMBER 1

PROCEEDINGS
of
The Institute of Radio Engineers

Form for Change of Mailing Address or Business Title on Page XLIII

Institute of Radio Engineers
Forthcoming Meetings

CINCINNATI SECTION
January 13, 1931
February 17, 1931

NEW YORK MEETING
February 4, 1931

ROCHESTER SECTION
January 15, 1931

SAN FRANCISCO SECTION
January 21, 1931

PROCEEDINGS OF
The Institute of Radio Engineers

Volume 19 | January, 1931 | Number 1

CONTENTS

PART I

PART II

Technical Papers

The Institute of Radio Engineers

GENERAL INFORMATION

The PROCEEDINGS of the Institute is published monthly and contains papers and discussions thereon submitted for publication or for presentation before meetings of the Institute or its Sections. Payment of the annual dues by a member entitles him to one copy of each number of the PROCEEDINGS issued during the period of his membership.

Subscription rates to the PROCEEDINGS for the current year are received from nonmembers at the rate of $1.00 per copy or $10.00 per year. To foreign countries the rates are $1.10 per copy or $11.00 per year.

Back issues are available in unbound form for the years 1918, 1920, 1921, 1922, and 1926 at $9.00 per volume (six issues) or $1.50 per single issue. For the years 1913, 1914, 1915, 1916, 1917, 1919, 1923, 1924, and 1925 miscellaneous copies (incomplete unbound volumes) can be purchased for $1.50 each; for 1927, 1928, and 1929 at $1.00 each. The Secretary of the Institute should be addressed for a list of these.

Discount of twenty-five per cent is allowed on all unbound volumes or copies to members of the Institute, libraries, booksellers, and subscription agencies.

Bound volumes are available as follows: for the years 1922 and 1926 to members of the Institute, libraries, booksellers, and subscription agencies at $8.75 per volume in blue buckram binding and $10.25 in morocco leather binding; to all others the prices are $11.00 and $12.50, respectively. For the year 1929 the bound volume prices are: to members of the Institute, libraries, booksellers, and subscription agencies, $9.50 in blue buckram binding; to all others, $12.00. Foreign postage on all bound volumes is one dollar, and on single copies is ten cents.

The 1930 Year Book, containing general information, the Constitution and By-Laws, catalog of membership, etc., is available to members at $1.00; to nonmembers, $1.50.

Contributors to the PROCEEDINGS are referred to the following page for suggestions as to approved methods of preparing manuscripts for publication in the PROCEEDINGS.

Advertising rates for the PROCEEDINGS will be supplied by the Institute's Advertising Department, Room 802, 33 West 39th Street, New York, N.Y.

Changes of address to affect a particular issue must be received at the Institute office not later than the 15th of the month preceding date of issue. That is, a change in mailing address to be effective with the October issue of the PROCEEDINGS must be received by not later than September 15th. Members of the Institute are requested to advise the Secretary of any change in their business connection or title irrespective of change in their mailing address, for the purpose of keeping the Year Book membership catalog up to date.

It is understood that the statements and opinions given in the PROCEEDINGS are views of the individual members to whom they are credited, and are not binding on the membership of the Institute as a whole.

All correspondence should be addressed to the Institute of Radio Engineers, 33 West 39th Street, New York, N.Y., U.S.A.

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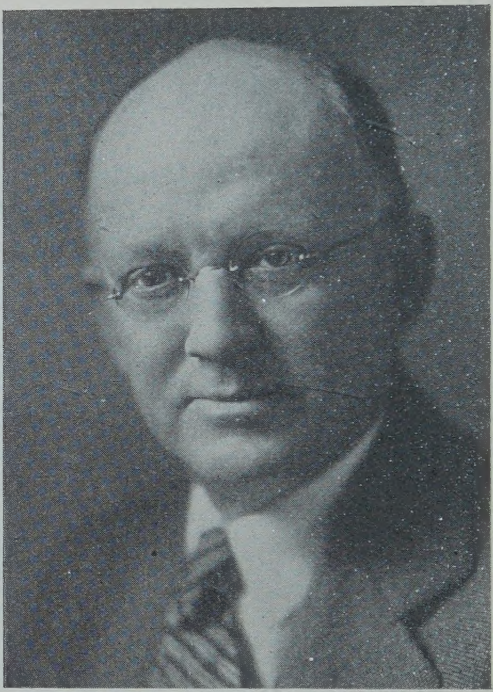

Harris and Ewing

Robert H. Marriott
First President of the Institute

Robert H. Marriott, first President of the Institute, founded the Wireless Institute in 1909 becoming its President until 1912 when it combined with the Society of Wireless Telegraph Engineers to form the Institute of Radio Engineers.

He was born in Richwood, Ohio on February 19, 1879. Graduating with the B.Sc. degree from Ohio State University in 1901, he entered commercial wireless engineering, completing in 1902 the first successful commercial circuit in the United States between Avalon, Catalina Island, and the California mainland. After continuing in commercial engineering work until 1912, he became U.S. Radio Inspector in the Department of Commerce. In 1915 he was transferred to the Navy Department as Expert Radio Aide. In 1925 he took up a private practice as a consulting engineer and served for a portion of 1928 and 1929 as a consulting engineer for the Federal Radio Commission. He has been responsible for a number of patents on radio subjects and has written many papers and articles on radio.

He is a Fellow of the Institute of Radio Engineers and of the American Institute of Electrical Engineers, an Honorary Member of the Radio Club of America and the Veterans Wireless Operators Association. At present he is a manager of the Institute, chairman of the Committee on Constitution and Laws, a member of the Committee on Broadcasting, and a member of the Committee on Admissions.

He is a representative of the Institute on the Sectional Committee on Definitions of Technical Terms of the American Standards Association and on the Council of the International Union for Scientific Radio Telegraphy as well as being a member of the U.S. Section of the International Radio Consulting Committee.

December Meeting of the Board of Direction

The December meeting of the Board of Direction was held on December 3rd at the office of the Institute, 33 West 39th Street, New York City. The following were in attendance: Alfred N. Goldsmith, acting chairman; Melville Eastham, treasurer; R. A. Heising, R. H. Marriott, A. F. Van Dyck, and Harold P. Westman, secretary.

Gilbert L. Bossard, R. E. Hantzsch, F. E. Johnston, and Joseph Kaufman were elected to the Member grade. W. E. Kierulff was transferred to the grade of Member.

One hundred and five applications for Associate membership and six applications for Junior membership were approved.

Radio Transmissions of Standard Frequency, January to June, 1931

The Bureau of Standards announces a new and improved service of radio standard frequency transmissions. This service may be used by broadcast and other stations in adjusting their transmitters to exact frequency, and by the public in calibrating frequency standards and transmitting and receiving apparatus. The signals are transmitted from the Bureau's station WWV, Washington, D.C. They can be heard and utilized by stations equipped for continuous-wave reception at distances up to about 1000 miles from Washington, and some of them at all points in the United States. This improved service is a step in the Bureau's program to provide eventually standard frequencies available at all times and at every place in the country.

Besides the usual monthly transmissions of specific frequencies, the Bureau will add another type of transmission which will be much more accurate than any previous transmissions by the Bureau. This transmission will be by continuous-wave radio telegraphy on a frequency of 5000 kc, and will consist primarily of a series of very long dashes. The first five minutes of this transmission will consist of the general call (CQ de WWV) and announcement of the frequency. The frequency and the call letters of the station (WWV) will be given every ten minutes thereafter.

Besides this service, the Bureau will also continue the transmissions once a month on scheduled specific frequencies. These are also by continuous-wave radio telegraphy. A complete frequency transmission includes a "general call," "standard frequency signal," and "announcements." The general call is given at the beginning of each 12-minute period and continues for about 2 minutes. This includes a

statement of the frequency. The standard frequency signal is a series of very long dashes with the call letters (WWV) intervening; this signal continues for about 4 minutes. The announcements follow, and contain a statement of the frequency being transmitted and of the next frequency to be transmitted. There is then a 4-minute interval while the transmitting set is adjusted for the next frequency.

Information on how to receive and utilize the signals is given in Bureau of Standards Letter Circular No. 280, which may be obtained by applying to the Bureau of Standards, Washington, D.C. Even though only a few frequencies are received (or even only a single one), persons can obtain as complete a frequency meter calibration as desired by the method of generator harmonics.

The 5000-kilocycle transmissions are from a transmitter of 150 watts power, which may be increased to 1 kilowatt early in the year; they occur every Tuesday except in those weeks in which the monthly transmissions are given. The monthly transmissions are from a transmitter of 1/2 to 1 kilowatt power; they are given on the 20th of every month (with one exception).

5000-Kilocycle Transmissions
1:30 to 3:30, and 8:00 to 10:00, P.M., Eastern Standard Time.

Jan.	Feb.	March	April	May	June
6	3	3	7	5	2
13	10	10	14	12	9
27	24	24	28	26	16
		31			30

Monthly Transmissions, Eastern Standard Time

Time	Jan. 20	Feb. 20	March 20	April 20	May 20	June 22
10:00 P.M.	1600	4000	550	1600	4000	550
10:12	1800	4400	600	1800	4400	600
10:24	2000	4800	700	2000	4800	700
10:36	2400	5200	800	2400	5200	800
10:48	2800	5800	1000	2800	5800	1000
11:00	3200	6400	1200	3200	6400	1200
11:12	3600	7000	1400	3600	7000	1400
11 24	4000	7600	1500	4000	7600	1500

The frequencies in the 5000-kilocycle transmission are piezo controlled, and are accurate to a few parts in a million. The frequencies in the monthly transmissions are manually controlled, and are accurate to a few parts in a hundred thousand.

In November, 1930, field intensity measurements were made of the 5000-kilocycle transmissions from WWV on 150 watts between Washington and Chicago. The daytime field intensity up to a distance of about 400 miles from Washington was about 100 microvolts per meter, with fading in the ratio 3 to 1. From this distance to Chicago the field intensity gradually decreased to about 10 microvolts per meter peak values with fading the same as above. The evening transmissions

had a field intensity of about 200 microvolts per meter with fading similar to that in the daytime. Around 8 P.M. the received intensity was sometimes too low to measure. This happened at distances of from 75 to 150 miles from Washington.

The Bureau of Standards would like to have detailed information on the reception of the 5000-kilocycles transmissions, and will appreciate receiving reports from any observers on their reception of these transmissions. Phenomena of particular interest are approximate field intensity, and fading (whether slow or rapid, and approximate time between peaks of signal intensity). The Bureau would also like to receive comments on whether or not the transmissions are satisfactory for purposes of frequency measurement or control. Reports on the reception of the transmissions should be addressed to Bureau of Standards, Washington, D.C.

Committee Work

Committee on Admissions

A meeting of the Committee on Admissions was held at 9:30 A.M. on December 3rd at the office of the Institute.

Six applications for transfer to the grade of Member and eight applications for admission to the grade of Member were investigated and approval was granted to three in each class.

Committee on Membership

A meeting of the Committee on Membership attended by I. S. Coggeshall, chairman; C. R. Rowe, J. E. Smith, and A. M. Trogner was held at 5:30 P.M. on December 3 at the office of the Institute.

Committee on Sections

At 7 P.M. on December 1st a meeting of the Committee on Sections was held. It was attended by Austin Bailey, chairman; C. W. Horn, B. E. Shackelford, and Harold P. Westman, secretary.

The proposed new Constitution prepared by the Committee on Constitution and Laws was considered in so far as it affected the operation of Institute Sections. The comments of the Committee will be presented to the Board of Direction when it reviews the proposed Constitution.

STANDARDIZATION

Technical Committee on Radio Receivers—I.R.E.

At 10 A.M. on December 4th a meeting of the Technical Committee on Radio Receivers of the Institute's Committee on Standardization

was held. The chairman, E. T. Dickey, C. M. Burrill, Virgil M. Graham, V. Ford Greaves, F. X. Rettenmeyer, and B. Dudley were in attendance.

SUBCOMMITTEE ON HIGH-FREQUENCY RECEIVERS OF THE TECHNICAL COMMITTEE ON RADIO RECEIVERS—I.R.E.

A meeting of the above Subcommittee was held at 10 A.M. on November 14th and was attended by C. M. Burrill, H. O. Peterson, F. A. Polkinghorn, and B. Dudley, secretary.

SUBCOMMITTEE ON MISCELLANEOUS TESTS OF THE TECHNICAL COMMITTEE ON RADIO RECEIVERS—I.R.E.

A meeting of the above Subcommittee was held at 9:30 A.M. on November 25th and was attended by F. X. Rettenmeyer, Harry Diamond, and Beverly Dudley, secretary.

Institute Meetings

CHICAGO SECTION

The October 23rd meeting of the Chicago Section presided over by S. E. Adair, vice chairman, was given over to a tour of the studios of the National Broadcasting Company which are located in the new Marshall Field Merchandise Mart. Unfortunately the attendance of two hundred and ten members and guests was much larger than was anticipated and it was not possible to devote as much time to the technical discussions of the equipment as was hoped would be available.

CLEVELAND SECTION

The November meeting of the Cleveland Section was held on the 21st of the month at the Case School of Applied Science, D. Schregardus, chairman, presiding.

A paper on "Radio Aids for Aircraft" was presented by Robert S. Shankland, formerly with the Bureau of Standards. The speaker described how a beam from two or more antennas is used to indicate to the pilot when he is off his course. Methods whereby one set of antennas can be arranged to give several courses at the same time were discussed. The equipment used on aircarft was described. Many points were illustrated with slides which were kindly loaned by the Bureau of Standards for that purpose.

The meeting was attended by forty-five members and guests.

LOS ANGELES SECTION

The November 17th meeting of the Los Angeles Section was held at the Rosslyn Hotel and presided over by Acting Chairman T. E. Nikirk.

A paper by J. I. Skov on "Problems in the Installation of Radio Compass Systems on Shipboard" was followed by a brief talk on aircraft radio compass equipment presented by Mr. Kennedy who was formerly of the T.A.T. The papers were discussed by Messrs. Alverson, Anderson, Athers, Comyns, and Ludlum.

The meeting was attended by one hundred and one members and guests.

New York Meeting

The New York meeting of the Institute was held on December 3, 1930, in the Engineering Societies Building, 33 West 39th Street.

Two papers were presented at this meeting. These are summarized below:

"Diversity Receiving System of R.C.A. Communications Inc. for Radio Telegraphy" by H. H. Beverage and H. O. Peterson. The early problems confronting the users of short wavelengths for communications are enumerated. Chief of these were fading and noise level. The phenomenon of fading is explained and the known methods of counteracting it are given. The most outstanding of these is the diversity principle. The various forms of this method are described and reasons developed for the choice of the particular form now in common use. The apparatus in general use is described in detail. In this system three spaced antennas are connected to three separate receivers. The output of each is rectified. The d-c outputs of all three receivers are combined in a common resistor, the drop in which is used to actuate means for controlling a locally generated tone which may be transferred to the receiving operator over a wire circuit. Since fading is not simultaneous in all three of the spaced antennas, a material reduction in the effects of fading is obtained.

"An aperiodic form of directive receiving antenna is described. Polar diagrams showing its directivity are presented. A series of measurements indicates a gain in signal-to-noise ratio on the order of 32 db for the European circuits as compared to a horizontal doublet.

"The effects of echo and cosmic disturbances are briefly discussed."

"Diversity Telephone Receiving System of R.C.A. Communications, Inc." by H. O. Peterson, H. H. Beverage, and J. B. Moore. Difficulties encountered in the reception of high-frequency radio telephone signals are described; the chief of these being fading and noise. General methods of solving these difficulties are discussed and the most desirable ones pointed out. The utilization of space diversity of fading is then taken up and methods of applying this principle to the reception of telephone signals are discussed. The method chosen is next described with reasons for the choice and explanation of the circuits and action of the system.

"A description of the general features of the equipment is given, and this is followed by a detailed consideration of the individual units comprising the double detection receivers and the combining and control equipment. Over-all characteristics are then given of selectivity and fidelity and a statement of sensitivity and minimum signal strength for commercial service.

"Improvement obtained by the use of this system is discussed, and the uses to which it is being put are stated. The latter include international rebroadcasting and transoceanic telephone service."

Several phonograph records illustrating the gain of reception due to the special types of these receiving systems were played.

The attendance at the meeting totaled four hundred members and guests.

Philadelphia Section

The October 29th meeting of the Philadelphia Section, which was held at the Engineers Club in Philadelphia, was presided over by W. R. G. Baker, chairman.

The meeting was opened with music furnished by an Orthophonic phonograph which was followed by a description of the Theremin. Several selections were played upon this instrument, the accompaniment being furnished by the phonograph. Test records were then demonstrated, giving the natural reproduction of music which was then repeated with frequencies above 3700, 2800, 1950, and 1000 cycles, respectively, being suppressed. Other test records compared natural speech with overloaded speech and various values of output.

This was followed by a demonstration of the newest models of the Philco receivers together with a demonstration of the Victor home-recording combination. Broadcast programs were recorded and played from records and sample records were made by many of the members present.

A demonstration of "speech reversal" was given. In this, words were pronounced correctly by the engineer in charge of the demonstration, and followed by the same words pronounced backwards. A photofilm was made of this and two negatives prepared, one of them being reversed and attached to the end of the film. When projected through the reproducer the film first reproduced the words as pronounced and then the reversed film converted the correct pronunciation into the backward pronunciation.

Several sound pictures were shown illustrating the various methods of sound recording. In addition a transmitter and receiver were exhibited to illustrate the method of sending facsimile copies of documents via high-frequency radio and the meeting closed with an appeal for old-type radio apparatus to be assembled into exhibits and placed in the Smithsonian Institute.

The meeting was attended by two hundred and eighty members and guests.

A meeting of the Philadelphia Section was held on November 18th at the Franklin Institute, C. D. Haigis, vice chairman, presiding.

O. H. Caldwell, editor of "Electronics" presented a paper on "The Electron in Harness." This paper which was illustrated with slides dealt with the multitudinous applications of the vacuum tube in industry, medicine, astronomy, etc. Interesting descriptions were given of many devices which have been developed.

The second paper of the evening was by C. N. Johnson, Westinghouse Electric and Manufacturing Company, and was a demonstration of several of the devices discussed by Mr. Caldwell. This included the Stroboglow oscillator and several phototube devices used for smoke control, counting, etc. Immediately following the demonstration, the one hundred and forty-eight members and guests were invited to examine the equipment and ask any questions concerning it that occurred to them.

Pittsburgh Section

A meeting of the Pittsburgh Section was held on November 15th and was devoted entirely to an inspection trip to the studios of KDKA and the transmitting station at Saxonburg, Pa.

At 1:00 P.M. the members and guests congregated at the KDKA studios located on the 21st floor of the William Penn Hotel. After signing the studio register they were conducted to the studio offices by P. A. Boyd. They were then conducted through the studio control rooms by D. W. Myer who described the intricacies of the control operating equipment.

At 2:15 P.M. after all had inspected the studios and control room, the party motored to the transmitting station located at Saxonburg in forty automobiles supplied for the occasion by the various members.

At the station, S. D. Gregory, E. M. Sollie, and D. W. Myer conducted the visitors around explaining the various details and answering all questions asked. Those of the members who walked out to the antenna system, which is located some distance from the transmitter, were welcomed by H. Roese, D. Stanier, and H. W. Irving who discussed that portion of the station.

About 5:00 P.M. all were through with the sight-seeing and the parties had left Saxonburg for the return trip. This trip proved to be highly interesting and educational. The attendance at the studio of fifty-five and at the station of seventy marks a new high level for the Section.

Rochester Fall Meeting

The Rochester Fall Meeting of the Institute was held at the Sagamore Hotel in Rochester on November 21st.

The morning was devoted to registration and the presentation of two technical papers as follows:

"The 227 Equi-Potential Cathode Tube" by A. C. Rockwood of the Hygrade Lamp Company.

"Notes on Circuit Design" by Fulton Cutting of the Colonial Radio Corporation.

Those attending the luncheon at noon were addressed by Vice Mayor Isaac Adler who as the official representative of the City of Rochester made the visiting guests welcome.

During the afternoon three papers were presented:

"Some Considerations in Superheterodyne Design" by David Grimes of the Radio Corporation of America.

"A New Low-Distortion Radio Amplifier Tube, Type 551" by Stuart Ballantine and H. A. Snow of the Boonton Research Corporation.

"The Thyratron; What It Is, and What It Does" by J. C. Warner of the General Electric Company.

The dinner at 6:30 P.M. was terminated by a demonstration of home-recording equipment and the playing of several records indicating the effect of certain specified distortions upon speech and music.

The evening session was devoted to but one paper on "Extending the Radio-Frequency Spectrum" by A. Hoyt Taylor, former President of the Institute.

The total registration at the meeting was 200, of whom 114 were indicated to be out-of-town guests. Sixty different radio munufacturing companies and ten educational, governmental, and professional institutions were represented at the meeting. The maximum attendance at any session totaled 225.

All arrangements for this meeting were under the direction of R. H. Manson, general chairman.

San Francisco Section

A meeting of the San Francisco Section held at the Engineers Club, San Francisco, was presided over by Walter D. Kellogg on November 19th.

A paper on "The Evolution of a Radio Magazine" was presented by Arthur H. Halloran who reviewed briefly the history of radio magazines in general showing the rise and fall in a number of publications from 1915 to the present time. He then outlined the trend and changes necessitated by popular demand. The interesting discussion of the mechanical operations necessary in getting an issue into print had

included in it many humorous incidents regarding contributions to the editorial department of the publication.

The attendance at the meeting totaled twenty-four.

Seattle Section

A meeting of the Seattle Section was held on October 10th in the Hotel New Washington, Austin V. Eastman, chairman, presiding.

A paper on the "Design of Transformers to be Used with Screen Grid Tubes as Intermediate-Frequency Amplifiers" was presented by Austin V. Eastman. This paper is a continuation of a similar paper, prepared by Mr. Eastman last spring and deals with the design of intermediate coupling transformers for use in superheterodyne receivers employing screen grid tubes.

The effect of changes in coupling, the variation of ratios, spacing, size of wire, etc. in the design of these transformers were discussed in detail.

After this paper, a motion picture showing the manufacture of Majestic radio receivers was shown.

The attendance totaled one hundred and four members and guests.

The November 21st meeting of the Seattle Section was held at the University of Washington in Seattle, Austin V. Eastman, chairman, presiding.

A paper by L. C. Austin on "Outline and Use of Broadcast Service Equipment" was presented. This paper described some of the present-day broadcast servicing equipment as well as several special devices which are not available as standard equipment from manufacturers. In outlining the use of this equipment, the speaker illustrated various points by applying the equipment to various broadcast receiver chassis and loud-speakers.

Messrs. Eastman, King, Kruse, and Murray of the seventy-six members and guests in attendance took part in the discussion.

Toronto Section

The Toronto Section held a meeting in the Electrical Building of the University of Toronto on October 15th. The Chairman of the Section, J. M. Leslie, presided.

Through the courtesy of the Film and Slide Company of Toronto and C. L. Richardson, the motion pictures taken of the Institute Convention held in Toronto were shown.

A general review of the Convention was made by Convention Chairman A. M. Patience who thanked the members for the excellent support given.

The first speaker of the evening, W. H. Kelterborn, Radiotron Engineer of the Canadian Westinghouse Company at Hamilton, delivered a paper on the "Manufacturing Problems Encountered in Vacuum Tube Production." A display of many early types of tubes was available for examination by the audience.

The second paper of the evening by F. K. Dalton, vice chairman of the Section, was a symposium on television, outlining developments in this field to date.

The attendance at the meeting totaled seventy-four.

Washington Section

Dr. L. P. Wheeler, chairman, presided at the November 13th meeting of the Washington Section held in the Continental Hotel.

A paper on "The First and Second Meetings of the International Technical Consulting Committee on Radio Communications" was presented by Gerald C. Gross, radio engineer of the Federal Radio Commission.

The speaker gave an outline of the work being done by the Committee.

The principal points discussed concerned designation of the various regions of the frequency spectrum as being low, intermediate, high, etc., the amount of tolerance necessary at different frequencies and for different classes of service, methods of measuring the power of a transmitter, classification of frequencies, and the necessity of holding closer to assigned frequencies.

The desirability and difficulties involved in maintaining an international standard of frequency were discussed.

The paper was discussed by Dr. Taylor and Dr. Wheeler, Captain Hooper, Professor Robinson, and Messrs. Burgess, Butman, and Davis of the forty-two members and guests in attendance at the meeting.

Personal Mention

E. C. Ballantine has been transferred from the Radio Engineering Department of the General Electric company to the Photophone and Applications Division of the RCA-Victor Company at Camden.

S. A. Bokovoy, formerly of the Westinghouse Electric and Manufacturing Company at East Pittsburgh is now a radio engineer for the RCA-Victor Company at Camden.

R. J. Cotton, a junior radio inspector for the Department of Commerce, Radio Division, has been transferred from Seattle, Wash., to Portland, Ore.

Formerly with the General Electric Company, M. L. Douthet is now in the engineering department of the RCA-Victor Company at Camden.

Captain P. P. Eckersley previously with the Marconiphone Company is now associated with the Dubilier Condenser Company in London, England.

V. J. Freiermuth an engineer for the Pacific Telephone and Telegraph Company has been transferred from New York City to San Francisco, Calif.

Captain R. A. H. Gailbraith, formerly of the Royal Canadian Signals, Department of National Defense, Ottawa, Canada, is now Commandant of the Military College of Science, Radio Barracks, Woolwich, England.

Paul C. Gardiner a radio engineer for the General Electric Company has been transferred from Oakland, Calif., to Schenectady, New York.

T. R. Gilliland previously a junior scientist at the Radio Section of the Bureau of Standards has become a graduate student in the Engineering School at Harvard University.

C. A. Gunther has joined the special apparatus division of the RCA-Victor Company at Camden, previously being connected with the General Electric Company at Schenectady, New York.

W. J. Gunther, formerly chief engineer of the World Battery Company is now chief engineer for the Johnson-Kennedy Radio Corporation at Gary, Ind.

J. R. Harrison, previously in the Department of Physics at the University of Pittsburgh, has recently joined the staff of Wired Radio at Ampere, N. J. as an assistant physicist.

H. C. Hogancamp has left the Technical Radio Laboratory of Paterson, N. J. to join the radio staff of the Pacent Reproducing Company of New York City.

H. W. Kitchin, Lieutenant, U. S. N., has been transferred from the U. S. S. Texas to the high power radio station at Annapolis, Md. where he is now officer in charge.

Previously a radio engineer at the Iowa State College broadcast station WOI, P. A. Konkle is now a telephone engineer for the RCA-Victor Company at Camden.

B. Leferts is now a design engineer for the United Research Corporation at Long Island City, New York, previously being plant and research engineer for the General Iustrument Corporation.

Formerly factory manager for the United States Radio and Television Corporation, F. L. Lemm has become factory manager for Story and Clark Radio Corporation at Grand Haven, Mich.

Paul S. Lester has joined the engineering department of the RCA Radiotron Company at Harrison, N. J.

H. M. Lewis has left the Signal Corps Laboratories at Fort Monmouth N. J. to become a senior radio engineer with the Hazeltine Corporation at their Bayside, L. I., laboratory.

Formerly engineer in charge of broadcast station WOMT, R. A. Limberg is now a field engineer for the National Broadcasting Company.

W. C. Little, formerly in the Radio Test Department of the General Electric Company has become operations engineer of the Northern Electric Company of Montreal, Canada.

Leaving the General Electric Company as a radio engineer, W. L. Lyndon has become transmitter division engineer for the RCA-Victor Company of Camden.

Carlton F. Maylott, formerly in the Department of Engineering of Lehigh University has joined the radio engineering department of the Bell Telephone Laboratories in New York City.

J. L. McLaughlin is now chief engineer for broadcast station WRNY previously being design engineer.

L. S. Nargaard, formerly a vacuum tube engineer in the Research Laboratory of the General Electric Company, has joined the Physics Department of the University of Minnesota as an teaching assistant.

D. O. Nichols previously with broadcast station WWAE has become chief engineer for the Sound Projection Co. of Chicago, Ill.

A. A. Ramsay has left the engineering department of the Brunswick-Balke-Collender Company of Los Angeles to become general manager of Amplifiers, Ltd., of Emeryville, Cal.

F. W. Schor, formerly with the Temple Corporation is now engineer for the Grigsby-Grunow Company of Chicago.

E. O. Selby has left the General Electric Company at Schenectady to join the radio engineering department of the RCA-Victor Company at Camden.

E. R. Shute, formerly operating engineer for Western Union Telegraph Company is now general superintendent of traffic at the new office, 60 Hudson St., New York City.

B. A. Somers has left the vacuum tube research laboratory of the General Electric Company at Schenectady to join the vacuum tube laboratory of the RCA-Victor Company at Camden.

L. C. Verman, formerly research assistant in the engineering research department of the University of Michigan, is now Heckscher research assistant at Cornell University.

J. S. Webb previously instructor in physics at Cornell University has become an associate professor in the department of radio engineering of the University of Minnesota.

PART II
TECHNICAL PAPERS

Proceedings of the Institute of Radio Engineers
Volume 19, Number 1 *January, 1931*

THE DESIGN AND CONSTRUCTION OF BROADCAST STUDIOS*

By
O. B. Hanson and R. M. Morris
(National Broadcasting Company, New York City)

Summary—*The science of sound, for years one of the most neglected of subjects related to physics, has during the past decade been the subject of much interesting research. A certain amount of impetus has been added to this work by the phenomenal growth of radio broadcasting owing to the necessity of providing studios suitable from an acoustic standpoint.*

This paper indicates certain facts relative to the science of acoustics and sound control and shows how they are applied in the construction of present day studios for radio broadcasting. Examples are given as well as methods of overcoming difficulties in practical application of principles.

IN THE past decade of radio broadcasting, tremendous strides have been made in development of equipment, methods of operation, and program technique chiefly due to the stimulus created by its rapid general acceptance by the public. We have constantly been faced with the problem of providing sufficient facilities, especially from a studio standpoint, to meet the increasing program traffic requirements of network broadcasting.

Ten years ago our ideas on broadcast studios were very meager compared to our knowledge and information of the present day. In 1923 what was believed to be quite an adequate studio layout for years to come consisted of two studios, one 22×35 ft. and one 16×20 ft. with a main control room common to both. Little, if any, time was spent on rehearsals in those days with the result that the two studios were sufficient to keep a continuous program on the air.

With the coming of sponsored broadcasting and the necessity for careful rehearsing and well worded announcements, much more time was devoted to rehearsals. As a comparison it might be interesting to note that on important programs it is now necessary to have anywhere from five to fifteen hours of rehearsal for one hour of program on the air. This fact accounts very largely for the increase in the number of studios required for one program channel today.

For the operation of two networks, which would obviously involve an elaborate plant, at least four studios would be required for program service alone and a number of others of varying size to handle rehearsals and auditions.

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Since nearly all rehearsals and auditions require practically the same studio conditions and apparatus necessary for program service, there is no particular point in providing studios for rehearsal purposes only. All studios should be made part of a common system for the creation of broadcast programs. The variation in number of performers and type of performances necessitate considerable variation in the size

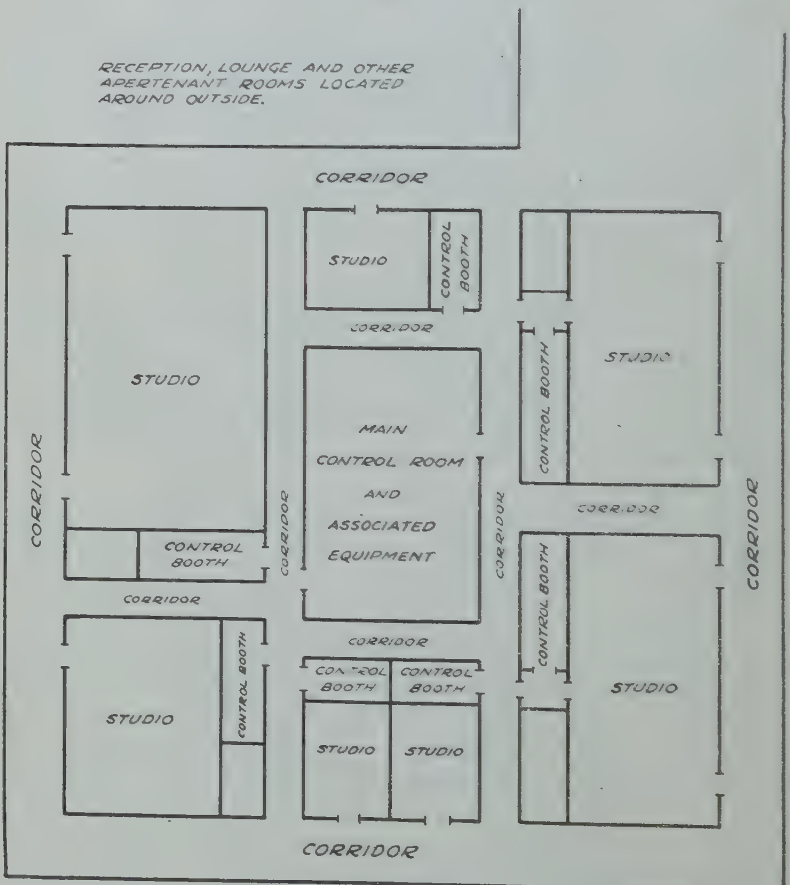

Fig. 1—Ideal studio plan.

of the studios. It is usually desirable that the same studio be used for broadcasting as for the rehearsal, in order that the carefully determined position of the instruments and microphone in the studio may be retained for the broadcast.

The problem of handling the increased number of musicians and performers becomes serious when it is possible that two or more pro-

grams may be conducted simultaneously, with several rehearsals also in progress in other studios. Such a condition might necessitate the presence of a total of three hundred or more musicians and other artists. It is necessary, therefore, to give serious thought to the placing of studios in order that they may be economically and efficiently operated not only from the technical standpoint, but also from that of reducing to a minimum the confusion which might exist among the musicians and visiting artists.

What is considered to be the ideal layout for a group of studios has been worked up from what may be referred to as a central control system. This consists primarily of a central main control room surrounded immediately by individual control rooms directly adjacent to their respective studios. The studios are approached on the opposite side by corridors through which the artists and performers may enter the studios. This makes for efficiency in the technical operation of the system and makes the studios readily accessible from a common point, for the production staff. An illustration of this fundamental plan is shown in Fig. 1.

It is obvious that with such a layout great pains must be taken in insulating the individual studio units against the transmission of sound, in order that each studio unit may function satisfactorily without acoustical interference from adjacent studios. Obviously any failure of the sound insulation system would render these groups useless. It is not only imperative that sound originating within the studio be kept within the desired bounds, but also that noises originating perhaps outside the building be prevented from entering the studios. Such rigid requirements call for elaborate methods of sound control and indicate that studios should preferably be constructed without windows or openings to the exterior. If it is necessary to provide such openings in studio walls special consideration will have to be given to making them incapable of sound transmission to any appreciable degree.

A brief outline of requirements covering the design of a group of broadcast studios is given herewith:

(1) Location

The studio group should be located in that part of a metropolitan area which is most accessible to artists. This is, of course, adjacent to the theater and concert hall centers. In the case of New York City, this section would be bounded on the north by 59th Street, on the south by 42nd Street, on the east by Madison Avenue, and on the west by 8th Avenue. It is also desirable for a studio group to be located on a street well known to the general public.

(2) Type of building

It is desirable to locate in a building which is under construction, or on which construction has not yet begun, so that the steel work may be readily modified to provide the area (clear of columns or supports) necessary for large studios. Although a studio group could be built on the lower floors of the skyscraper type of building, this is not economical as the cost of steel spans to support the tall buildings would be prohibitive. If it is necessary to occupy a finished building, a location in the upper floor of the loft type of structure such as used for department stores and light manufacturing is probably most satisfactory.

(3) Sound insulation

Means must be provided to prevent the transmission of sound from one studio to another or from the outside into any studio. Studios should be built as a box within a box, the inner box mechanically insulated against vibration from the outer, and the outer, of course, supported on the steel structure. To be highly effective complete soundproofing necessitates that the studio floor, walls, doors and glass partitions be to all intents and purposes hermetically sealed.

(4) Air conditioning and ventilation

A ventilating system of the ordinary type is not sufficient for broadcast studios. Large groups of musicians rapidly increase the temperature and humidity necessitating that the air be replaced frequently with cooled and dehumidified air. To accomplish this, a system of air conditioning is necessary. A more detailed description of this system is given later on in this paper.

(5) Acoustic treatment

Perhaps one of the most important considerations as far as the production of the program itself is concerned is the acoustic condition within the studio. It is necessary to provide within the studio sufficient sound absorbing material to reduce the reverberation time to the desired optimum value. Variation in the amount of sound absorption should be provided for, to compensate for variations in the size of the musical groups. The acoustic material used should of course have a frequency-absorption characteristic satisfactory over the entire musical range.

(6) Lighting

The individual music stand lighting system used in concert work is not adapted to broadcast studios as the location and size of the groups performing are too varied. Lighting cables layed on the floor are also somewhat of a nuisance. The lighting, therefore, must

be from overhead and of sufficient strength to enable the musicians to read manuscript with ease. It has been found necessary to provide approximately 20 foot candles. Facilities must also be provided for supplying power to the portable flood lights used for taking photographs.

(7) Decoration of studios

Although this problem does not immediately concern the engineer except wherein it may affect the acoustic condition, considerable stress should be placed on the importance of the proper architecture and decoration of the studios. This has a psychological effect upon the mood of the artists which influences their performance. In some of the later designs of the NBC studios, the decoration has been rather elaborate.

(8) Technical operating requirements

In the design of the main control room equipment and the equipment which is associated with the individual studio control rooms, it must be borne in mind that all studio equipment should be electrically interlocked in order to provide the necessary flexibility. Any studio should be capable of instantaneous connection with the outgoing circuits at the will of the master transmission supervisor. In operating a centralized studio group, it is assumed that a control operator will be stationed in the studio control booth of each studio in use to control volume and monitor the outgoing programs, and that a supervisor will be located in the main control room to superintend general technical operation. It is not intended in this article to describe the technical apparatus used in connection with broadcasting but rather to describe in detail the design of studios and to discuss factors influencing this work.

The adaption of the ideal plan shown in Fig. 1 to an actual building should be of interest as an illustration. Of course definite rules can hardly be set down to govern application of principles. It is a matter of careful study and thought, in each individual case. Fig. 2 shows how the central control plan was adapted to the building occupied by the NBC at 711 Fifth Avenue, New York City. An even better idea can be obtained by reference to the cutaway view of the studio layout shown in Fig. 3. It is desirable of course to keep the studios on one floor if possible, but such is hardly economical at such locations as Fifth Avenue, due to limited floor area.

A description of the newly completed Chicago Studios of the NBC will further illustrate the foregoing principles.

Fig. 4 shows how the ideal layout was adapted to the building conditions found in the Merchandise Mart building. It will be noted

first of all that the studios vary in size but are of similar shape. It has been found that the studio dimensions have an influence on the acoustic conditions and from experience an empirical formula for determining this is worked out as follows:

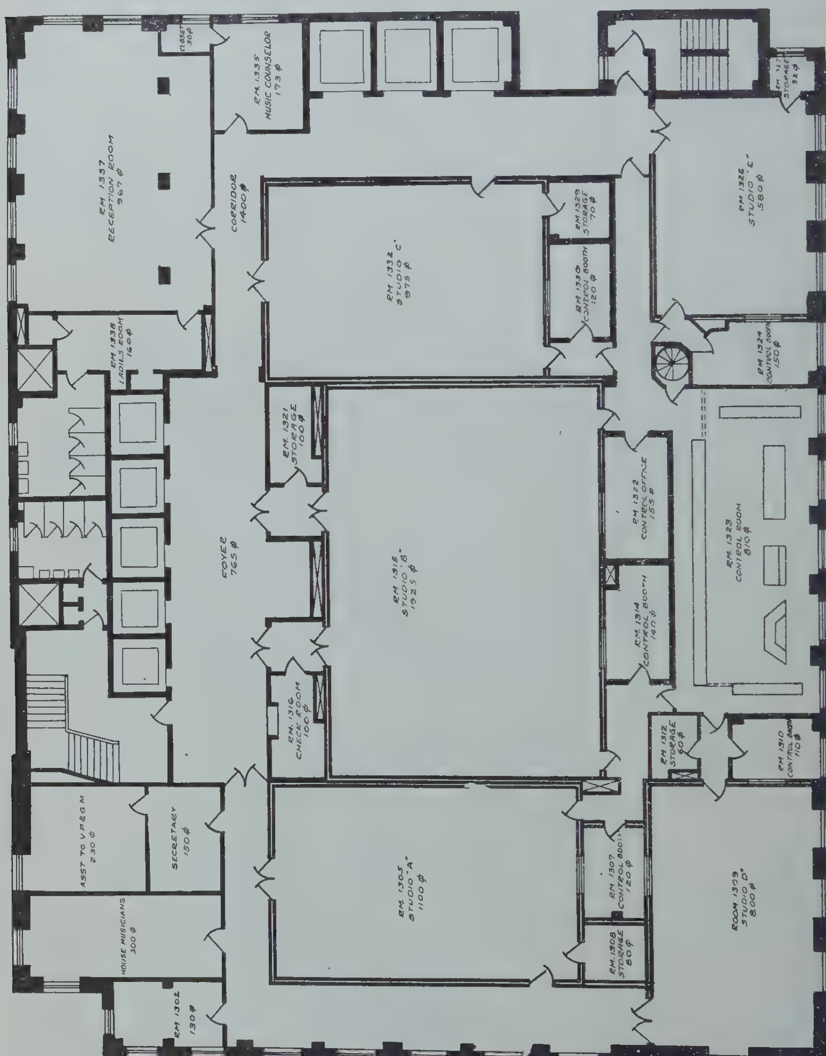

Fig. 2—Plan of 13th floor, 711 Fifth Avenue, showing arrangement of studios.

It has been found from experience that the dimensions of a studio to be most satisfactory from an acoustical as well as an esthetic consideration, should be approximately in the ratio 2–3–5 for the height, width, and length, respectively.

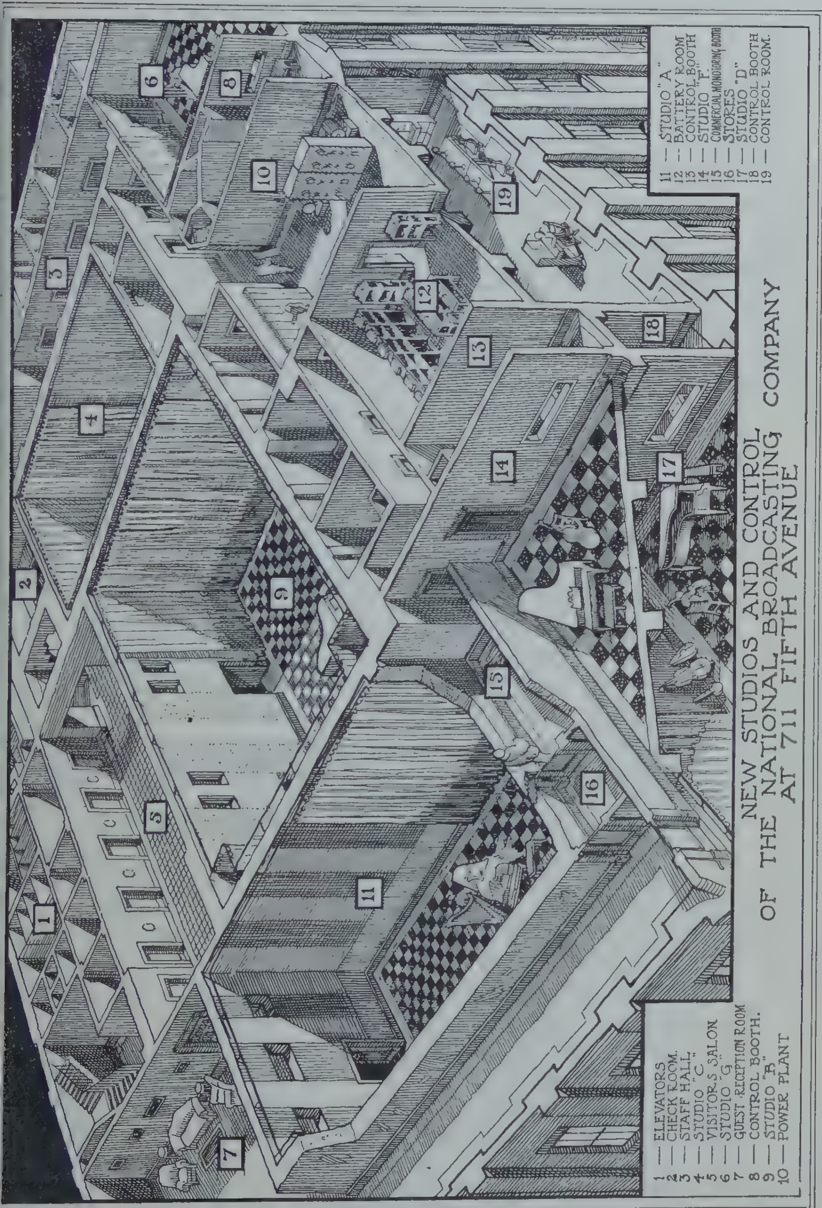
NEW STUDIOS AND CONTROL
OF THE NATIONAL BROADCASTING COMPANY
AT 711 FIFTH AVENUE
1 — ELEVATORS
2 — CHECK ROOM.
3 — STAFF HALL
4 — STUDIO "C"
5 — VISITOR'S SALON
6 — STUDIO "G"
7 — GUEST RECEPTION ROOM
8 — CONTROL BOOTH.
9 — STUDIO "B"
10 — POWER PLANT
11 — STUDIO "A"
12 — BATTERY ROOM
13 — CONTROL BOOTH
14 — STUDIO "F"
15 — COMMERCIAL MONITORING BOOTH
16 — STORES
17 — STUDIO "D"
18 — CONTROL BOOTH
19 — CONTROL ROOM.

Fig. 3.

Using this ratio the approximate dimensions of a studio in terms of its height are,

$$\text{width} = \frac{3}{2}h \tag{1}$$

$$\text{length} = \frac{5}{2}h \tag{2}$$

On first consideration it would seem that the capacity of a studio would be proportional to floor area. It has been found, however, that

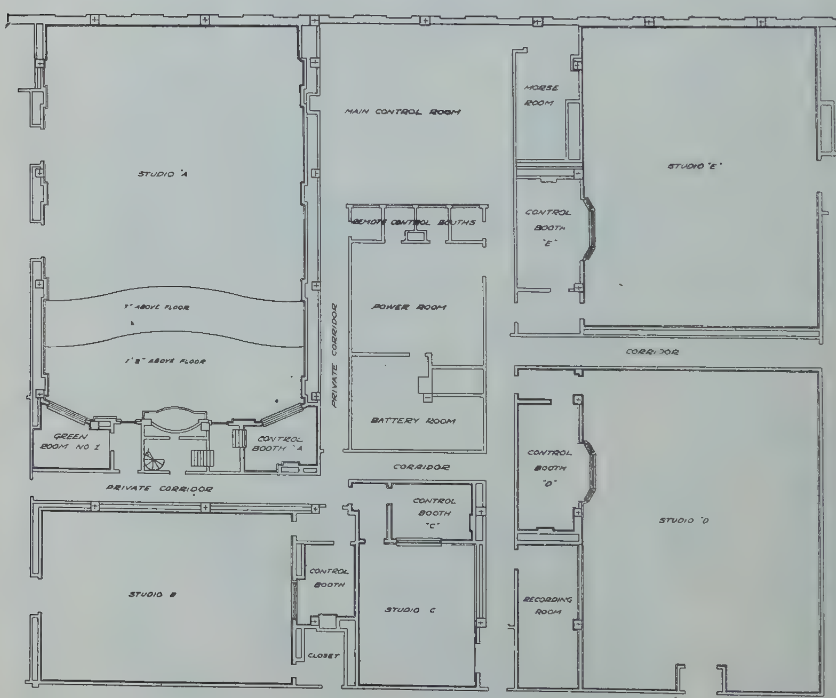

Fig. 4—Studio and control room layout—Chicago.

it is more nearly proportional to volume for two reasons. First, the ventilating requirements are directly proportional to the normal studio capacity and second, the floor area required per artist in the case of large groups is less than required in smaller groups due usually to the greater percentage of vocalists and artists playing the smaller instruments.

It is possible, therefore, to say that

$$V \propto N \tag{3}$$

or

$$V = KN \tag{4}$$

where V = Volume of studio in cubic feet
N = Number of artists constituting normal capacity.

From experience it has been found that

$$K = 750$$

therefore

$$V = 750N = \frac{15}{4}h^3 \tag{5}$$

$$h = 5.87\sqrt[3]{N} \tag{6}$$

In order that the minimum studio size shall have a ceiling height of not less than 8 feet

$$h = 8$$
$$\sqrt[3]{N} = 1.37$$
$$N = 2.55 \tag{7}$$

Expression in final form, therefore, is

$$h = 5.87\sqrt[3]{N - 2.5} \tag{8}$$

This relation is shown in graphical form in Fig. 5 which also gives the values of width and length. It should of course be remembered that these values are approximate and should be considered only as a guide. Construction limitations will probably be the deciding factor in the actual dimensions finally decided upon.

Table I gives in tabular form the dimensions of the Chicago group of studios to illustrate typical compromises which must usually be made. Dimensions of Studios C and F are notable for their deviation from the proper ratio, while Studios A and B fall rather close to the prescribed value.

TABLE I

STUDIO DIMENSIONS
CHICAGO INSTALLATION

Studio	Length	Width	Height
A	72′–0″	47′–0″	26′–6″
B	45′–6″	31′–2″	21′–6″
C	26′–0″	21′–0″	10′–0″
D	57′–2″	42′–0″	21′–6″
E	54′–1″	42′–0″	21′–6″
F	26′–0″	21′–0″	10′–0″

The building in which or upon which the Chicago Studios have been erected is of immense proportions, being considered the largest building in the world. The roof over the eighteenth floor has an area of approximately 200,000 square feet, so that there was ample space to erect a studio group without serious complication of the steel problem. With practically no restrictions on outside dimensions these studios were placed as desired, in the shapes desired, grouped around the central control room, and the exterior wall erected about the whole. It will be

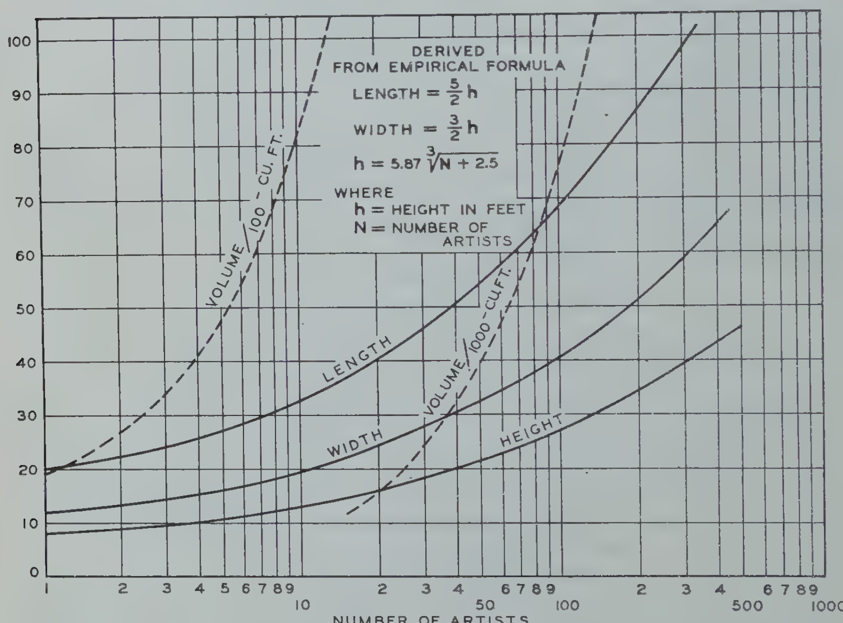

Fig. 5—Relation of studio capacity to studio dimensions and volume in standard broadcast practice.

noted by reference to the plan, Fig. 4, that each studio unit includes its individual control room, double entrance vestibules and an observation gallery, all of which are insulated against sound transmission from the other studio units. In addition to the floating floors, walls, and ceilings which were provided, corridors are placed between the studio units to assist further in sound insulation. No studio wall is immediately adjacent to that of another.

All studios are readily accessible from the central control point. Provisions for artists' entrance are on the side of the studio away from the control room, so that there is no cross traffic between performers and production and technical staff. In addition to the studios, ample space was provided for storage batteries, power supply, ventilating

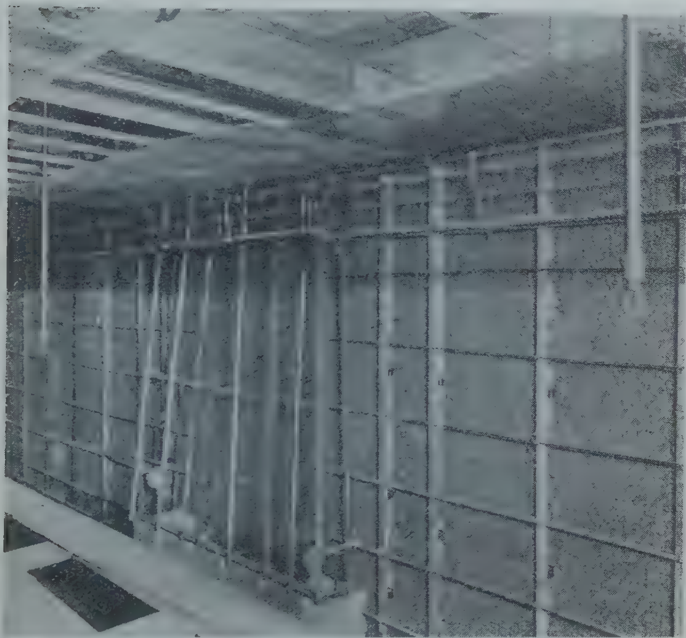

Fig. 6—View of soundproofing showing wall and ceiling.

Fig. 7—View of soundproofing on wall (close-up).

equipment, speech input equipment, and line terminal and switching equipment for the routing of network programs originating in other cities through the Chicago control room.

Acoustically treated monitoring booths in the control room are

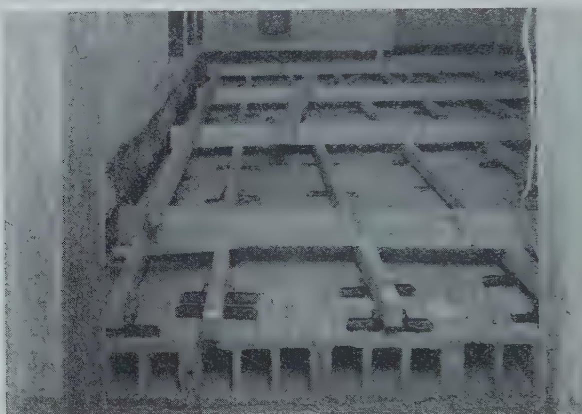

Fig. 8—View of floor without fill.

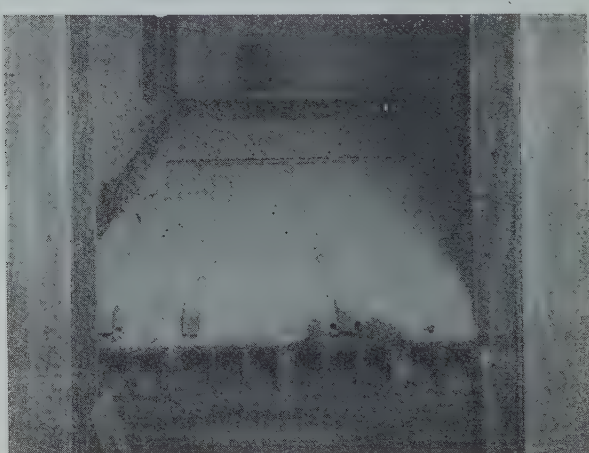

Fig. 9—View of floor with fill.

provided for the proper monitoring of through programs and for checking the transmission of network stations.

Following is a more detailed description of the system used in the Chicago plant of soundproofing studios and their individual control rooms, and the construction of transparent partitions and soundproof walls. The main walls of the studios are erected of a single layer of four-

inch terra cotta tile. On the studio side of these walls are placed steel spring clips on 18-inch centers and on these clips in turn is placed metal lath. (See Figs. 6 and 7.) The same treatment is applied to the ceiling. To prevent the possibility of reverberation in the space be-

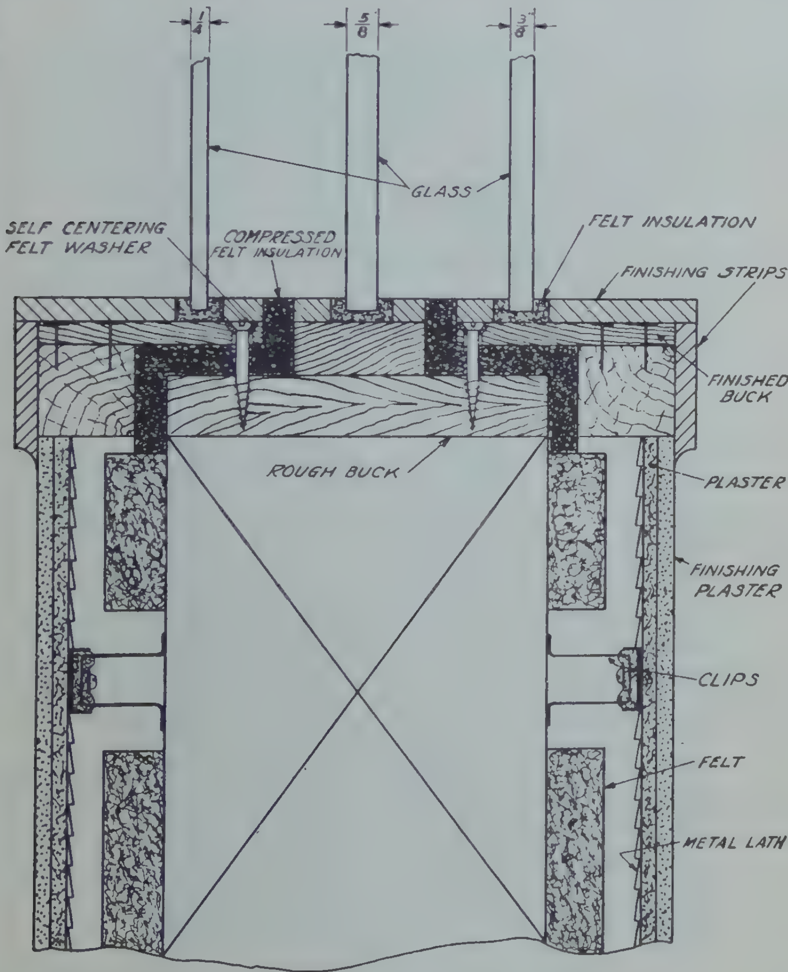

Fig. 10—Soundproof window construction.

tween the outer wall and the main terra cotta walls, hair felt or similar sound absorbing material is placed on the main wall in the spaces between the spring clips and the walls. This also applies to the area back of the hung ceiling. The ordinary layer of rough plaster is then applied to the metal lath and on top of this the acoustic treatment or hard plaster, as may be specified.

A similar system of soundproofing is placed upon the floor except that the springs in this case support wooden sleepers. Before laying the wooden floor, the space between the concrete slab and the top of the wooden sleepers is filled with some light sound absorbing material, such as mineral wool or thermo-fill, to prevent resonance in the floating floor. (See Figs. 8 and 9.)

This construction provides walls, floors and ceilings which are floating on spring clips. The attenuation to sound originating in the studio through such a partition when completed is approximately sixty decibels, even at frequencies as low as sixty-four cycles. The attenuation of course is much greater at the higher frequencies. This same soundproofing treatment is applied to the walls of the adjacent control booths so that the sound insulation is doubly effective between the studio and its control booth, which aids in eliminating interaction between the loud-speaker operating in the control booth, and the microphone and permits monitoring without acoustic interference from the studio.

The necessity for a transparent partition between each studio and its control room presents somewhat of a problem to obtain attenuation comparable with the walls themselves. Three pieces of glass of varying thicknesses, namely, 1/2 in., 3/8 in., and 1/4 in. are used in this partition, each piece mounted on a separate buck, the bucks in turn being mounted, one on the terra cotta partition and the other two on their respective floating partitions. Figs. 10 and 11 show this construction in more detail. Three different thicknesses of glass are used to stagger the natural period of the panels, which helps considerably in increasing the attenuation. The system of soundproofing described may be compared in its action to an electrical filter.

The installation of such an elaborate method of soundproofing may seem overcautious, but the success or failure of the studios when put in operation are dependent upon this factor. Even from the economic point of view, however, this is less expensive than the erection of double terra cotta or brick walls and more effective due to separation of the floor from the main structure.

A number of tests were conducted on various makes of doors suitable for studio use and a door was built, to the NBC's specifications, of comparatively light construction which has an attenuation of approximately forty decibels. The entrance to all studios is through vestibules with a soundproof door at each end. This gives in effect a sound lock analogous to an air lock to a pressure chamber so that access to studios in operation is possible. The vestibules are treated acoustically to have high sound absorption. The attenuation through such

doors and vestibule is even in excess of that of the studio partitions. It is possible to erect doors of such weight and dimensions that only one door is necessary, but such is not practical. In placing the doors, great care must be exercised to see that proper contact is made against

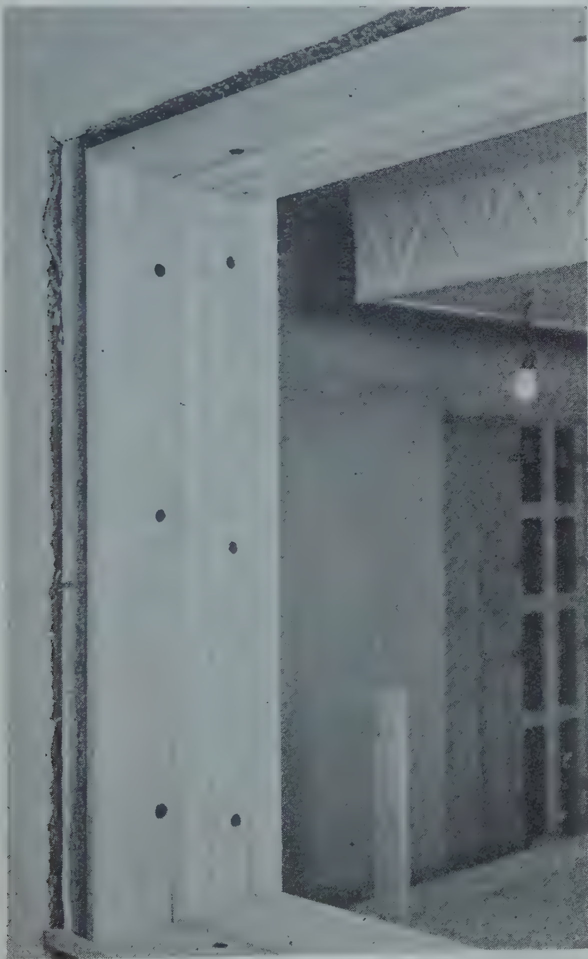

Fig. 11—View of soundproof window frame.

the jambs, two of which are provided. The door when closed is practically air-tight, even at the floor.

The system of ventilation in the Chicago studios is that manufactured by the Carrier Engineering Corporation. A detailed description of this ventilation system is not necessary, as its operation is well

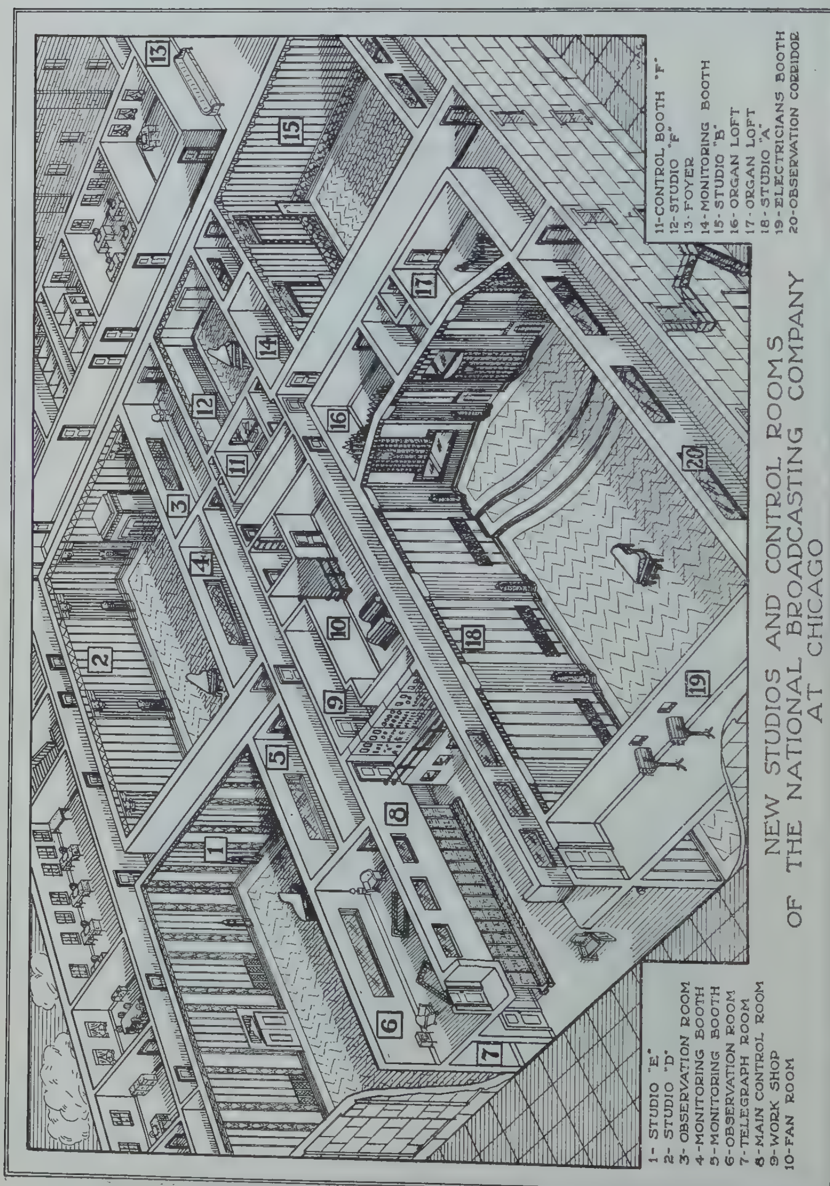
1- STUDIO "E"
2- STUDIO "D"
3- OBSERVATION ROOM
4-MONITORING BOOTH
5-MONITORING BOOTH
6-OBSERVATION ROOM
7-TELEGRAPH ROOM
8-MAIN CONTROL ROOM
9-WORK SHOP
10-FAN ROOM
11-CONTROL BOOTH "F"
12-STUDIO "F"
13-FOYER
14-MONITORING BOOTH
15-STUDIO "B"
16-ORGAN LOFT
17-ORGAN LOFT
18-STUDIO "A"
19-ELECTRICIANS BOOTH
20-OBSERVATION CORRIDOR
NEW STUDIOS AND CONTROL ROOMS
OF THE NATIONAL BROADCASTING COMPANY
AT CHICAGO

FIG. 12.

known to engineers. It might be well, however, to mention the peculiarities of the system which adapt it to broadcast studios. The most important factors are the prevention of transmission of sound through the metal work of the ducts themselves and through the air columns within the ducts. The former is taken care of by wrapping the outside of the ducts with a sound absorbing material to damp the vibrations of the metal walls. A system of sound absorbing baffles are used within the ducts to prevent transmission through the air column. These are of course installed in both the supply and exhaust ducts and are placed where they will be most effective in preventing the transmission of sound in either direction. This makes a cross section of the duct appear honeycombed, except that the partitions are square instead of hexagonal. These muffler sections are approximately fifteen feet in length. The acoustic material used is a form of Mexican moss wrapped in a membrane to prevent it from being scattered throughout the duct. Other forms of acoustical treatment, of course, could be used. Actual baffles built of sound absorbing boards erected similar to an automobile muffler were used in the New York studios of the NBC but these, although equally effective, occupy more space and cause more resistance to air flow than the method used in the Chicago studios. Emphasis must be placed on the necessity of independent studio ducts back to the main fan and the provision of individual steam and air flow control. Individual temperature control is necessary as certain studios may be vacant while others may be in use to capacity, thus calling for a different incoming air condition for each studio.

It has been found from experience that it is rather difficult, in the matter of acoustic treatment, to obtain the desired and expected results solely on the basis of frequency-absorption characteristics as supplied by the manufacturers.

The essential reason for this is that such characteristics were determined under conditions differing from those under which the material is applied in the studio. This difference is particularly noticeable in the type of wall construction herein described. At the present time almost all existing determinations of frequency absorption characteristics of commercial acoustic treatments have been taken by the Sabine reverberation method using a chamber of solid masonry where transmission through the walls is negligible. In the case of studio walls the transmission through the floating partition to the acoustic treatment behind is far from negligible at frequencies below 250 cycles. There is also a certain amount of absorption at low frequencies in this partition, independent of acoustic treatment, due to actual motion under sound pressure. It is therefore desirable, since all present acoustic treatments

are somewhat deficient in low-frequency absorption, to apply an acoustic treatment which will reduce as little as possible the inherent effective absorption of the soundproof partition. From this standpoint an acoustic treatment therefore should have a low density and be non-rigid.

Tests conducted in experimental studios have shown increases in reverberation time at 64 cycles, of approximately 100 per cent due to application of an acoustic treatment not having these qualities. The actual figures in this case were 0.95 seconds before application and 1.9 seconds afterwards. Under identical conditions the application of a light, flexible, acoustic treatment caused a reduction in reverberation time from 1.0 second to 0.85 second.

The optimum reverberation time for broadcast studios is generally believed to be somewhat less than the standards set by Watson and Sabine for auditoriums mainly because of the fact that the acoustics of two rooms enter into the final result. A satisfactory value of reverberation time for studios of 2,000 to 3,000 cubic feet is approximately 0.7 seconds; for studios of 100,000 cubic feet, approximately 1.1 seconds.

It should be emphasized, however, that the type of music being rendered plays by far the greater part in the value of reverberation time giving most satisfactory results. Fast moving, stacatto selections require much less reverberation than is permissible, and in fact desirable, in the case of slow moving largo passages.

In general, two-thirds of the wall area is treated with acoustic treatment previously selected and found satisfactory for the purpose, the remaining third being treated with hard plaster of irregular surface. In the Chicago Studios the wall areas are broken up by pilasters of hard plaster, the pilasters in turn being V'd to break up the reflected wave front. The ceilings are also broken up with coffers of varied size.

It has been the purpose of this paper to outline briefly the problems encountered in the design and construction of studios suitable for radio broadcasting and to set forth practical solutions to the problems. This paper was prepared from experience in answering questions of others faced with this problem in the past, as well as from first-hand experience in the design of the studio groups mentioned. It is hoped that it may serve to some degree as a guide to those encountering this problem in the future.

Proceedings of the Institute of Radio Engineers
Volume 19, Number 1 *January, 1931*

ACCURATE METHOD OF MEASURING TRANSMITTED WAVE FREQUENCIES AT 5000 AND 20,000 KILOCYCLES PER SECOND*

By
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Summary—*The measurement of the frequency of a radio transmitting station offers a convenient means of intercomparison of frequency standards situated in different laboratories. While there have been several articles published dealing with station frequency measurements, these have, for the most part, considered frequencies in the broadcast band or lower. This paper describes a method of measuring station frequencies applicable to any frequency but dealing primarily with frequencies of approximately 5000 kc and 20,000 kc. A high order of precision is obtained by the use of harmonics and audio-frequency beat notes. Most of the units of the equipment employed have been previously described in connection with other applications.*

THE measurement of the frequency of a distant radio transmitting station offers a means of intercomparison of the frequency standards of two or more laboratories, which may be in different countries, and of calibrating secondary frequency standards in various laboratories. The above applications have been used with increasing accuracy as improvements in radio apparatus and technique of measurement have become available. However, the accuracy obtainable in the intercomparison of two frequency standards in this manner may be surprisingly good if suitable measurement methods are chosen, as will be shown later.

In 1923 and 1924 simultaneous measurements were made upon the transmissions of some of the transoceanic telegraph stations by two European laboratories and the Bureau of Standards. The agreement was of the order of 0.2 per cent.

The method of measurement described by Royden,[1] using a frequency meter, is stated to give readily an accuracy of 0.1 per cent. While the frequency range covered is not stated, measurements at 14.5 and 20 kc are mentioned.

A year ago the frequencies of the European broadcast stations were being measured with an accuracy of 0.02 per cent,[2] using the

* Decimal classification: R213. Original manuscript received by the Institute, June 14, 1930. Presented before April 25, 1930, meeting, American Section of the U. R. S. I., Washington, D. C. Published by permission of the Director of the Bureau of Standards of the U. S. Department of Commerce.

[1] George T. Royden, "*The frequency checking station at Mare Island*," Proc. I. R. E., **15**, 313–318; April, 1927.

[2] W. H. F. Griffiths, "Accurate wavemeter design," *Wireless World* (London), **26**, 113; January 29, 1930.

apparatus and methods described in papers by Braillard and Divoire.[3,4,5] Refinements not usually used were said to increase the accuracy of the method to a few thousandths of one per cent.

Frequency measurements upon broadcast stations as described by Bogardus and Manning[6] were made with an accuracy of about a hundredth of a per cent The same order of accuracy is obtained by the method used in Italy by Pession and Gorio.[7]

Radio transmitting sets of a few years ago had no means of accurately controlling the frequency such as is now possible with a piezo control which is maintained at a constant temperature. If a radio transmitting set can be relied upon to maintain its frequency quite accurately, it is no longer necessary that simultaneous frequency measurements be made in order to obtain accurate frequency comparisons. There are probably very few technicians accustomed to making frequency measurements of high precision, who would guarantee to make such measurements at definitely prescribed times, because of various kinds of interference which invariably occur at such times. This is true at least in a radio laboratory where several may be engaged on various kinds of testing work at the same time, and electric motors and other apparatus may be producing interference. However, if the transmitting set remains constant, measurements can be made as convenient, and consistent results can be obtained.

Some months ago the Bureau undertook to measure the frequency of the transmitted wave of NKF, Bellevue, D.C., which was approximately 20,085 kc. This transmitting set is piezo-controlled by a quartz plate with a frequency of approximately 2510 kc. Successive frequency doubling stages are employed. During preliminary measurements an antenna was temporarily connected in to the 5000-kc stage and then to the 10,000-kc stage, as well as to the final stage. The transmission could not be picked up on the 10,000-kc transmission, presumably because the Bureau was within the skip distance for this

[3] R. Braillard and E. Divoire, "The exact and precise measurement of wavelength in radio transmitting stations," *Experimental Wireless & Wireless Engineer*, (London), **4**, 322–330, 394–401, 1927.

[4] R. Braillard and E. Divoire, "How broadcasting wavelengths are checked. A description of the International Listening Station at Brussels," *Wireless World*, **22**, 219–222, 1928.

[5] R. Braillard and E. Divoire, "Measurement of wavelengths of broadcasting stations," *Experimental Wireless and Wireless Engineer* (London), **VI**, 412–421, 1929.

[6] H. L. Bogardus and C T. Manning, "The routine measurement of the operating frequencies of broadcast stations," Proc. I. R. E., **17**, 1225–1239; July, 1929.

[7] G. Pession and T. Gorio, "Measurement of the frequencies of distant radio transmitting stations," Proc. I. R. E., **17**, 734–744; April, 1929; Pession and Gorio, "Sulla Misura Della Lunghezza D'Onda," *Electrotecnica* (Italy), **15**, 524–530; 1928.

frequency and the ground wave was not of sufficient strength. As both the 5,000-kc and 20,000-kc transmissions could be picked up readily, it was thought desirable to have both these frequencies transmitted and use the measurements on one frequency as a check on the measurements at the other frequency. This was accomplished through the courtesy of Dr. Taylor and his associates at the Naval Research Laboratory.

The measurements here considered have been made upon special transmitted signals, the part used in measurement consisting of a long dash. While the method can be employed upon the keyed signal of a station, yet it loses precision in such a case, because it is difficult, if not impossible, to match a steady note precisely with an intermittent or broken note. Experience has shown the necessity of an identifying signal such as the station's call letters, but these should be kept to a minimum, and the dashes for measurement purposes made to predominate.

Most of the apparatus used in the measurements has been described in other papers.[8,9,10] The paper, reference 9, on testing piezo oscillators, states that the method described is also applicable to the measurement of station frequencies. Since the paper was prepared, the Bureau has obtained a very accurate primary standard of frequency, similar to that described by Marrison.[11] The frequency measurements are based upon this new standard rather than upon the standard mentioned in the previous reference.[9]

The method of measurement is the familiar one consisting of tuning a radio receiver to the frequency of the station to be measured, adjusting a radio-frequency generator to the same frequency or some harmonic of it, and measuring the frequency of the generator. The frequency relation between the generator and the radio receiver being known, the frequency of the signal is readily obtained.

In order to explain the refinements making for increased precision and accuracy in the measurements to be described, reference is made to Fig. 1. The radio receiver R is adjusted to the desired station signal, as for example, 5021 kc, and left in a nonoscillating condition. The

[8] E. L. Hall, "A system for frequency measurements based on a single frequency," Proc. I. R. E., **17**, 272–282; February, 1929.

[9] E. L. Hall, "Method and apparatus used in testing piezo oscillators for broadcasting stations," *Bureau of Standards Journal of Research*, **4**, 115–130, January, 1930; also as Research Paper No. 135, obtainable from Superintendent of Documents, Government Printing Office, Washington, D.C., for ten cents; Proc. I. R. E., **18**, 490–509; March, 1930.

[10] N. P. Case, "A precise and rapid method for measuring low frequencies," *Bureau of Standards Journal of Research*, August, 1930; Proc. I. R. E., **18**, 1586–1593; September, 1930.

[11] W. A. Marrison, "A high precision standard of frequency," *Bell Sys. Tech. Jour.*, **8**, 493–514; July, 1929; Proc. I. R. E., **17**, 1103–1122; July, 1929.

generator P is then adjusted to zero beat with the radio receiver, and a reading taken upon the frequency meter W. Generator P is then adjusted away from zero beat until beats are obtained by matching with the note from a tuning fork TF, which is held in the hand and struck with a small mallet as desired. A second reading is taken at this time upon the frequency meter W, the readings of which are used in recording the direction from zero beat where the precise measurement is made. Further discussion of the frequency at which generator P is set for the measurement will be given after describing the remainder of the procedure.

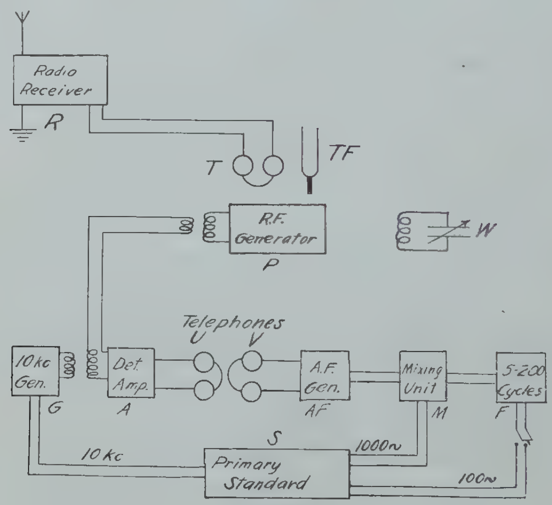

Fig. 1.

The 10-kc generator G is controlled by the primary standard S which supplies current at 10 kc. Generator G is of the Hartley type, having a grid resistor across which the control voltage is impressed. It remains in control over a considerable capacity change. Harmonics of the 10-kc generator G have been used in measurements as high as the 290th, but, generally speaking, harmonics below half this order are usually used.

The detector amplifier, described in a previous paper,[8] picks up the beat frequency between generator P and generator G, as heard in telephones U. This beat frequency is matched with a similar frequency from the audio-frequency generator AF, as heard in telephones V, at a time when the setting of generator P gives a beat note in the telephones T matching tuning fork TF.

The characteristics of the generator AF are such that it will

maintain its frequency over long periods. However, the calibration is not relied upon, and the output is sent into a mixing unit M or modulator, which also receives a frequency of one thousand cycles per second from the primary standard S. The resulting beat frequency output from M is sent into the direct reading frequency meter F, described in a previous reference,[10] which is checked against the hundred cycles per second output of the primary standard S. The frequency meter F is limited in range from 5 to about 200 cycles per second, but by use of the modulator M and the 1000-cycle output from S, measurements in this range around the harmonics of 1000 cycles per second can be made.

If it is desired to measure a frequency of approximately 20,085 kc, for example, with generator P set at such a frequency, the detector amplifier A could hardly be expected to pick up the 2008th harmonic of generator G. If it did, there would be an audio-frequency note of 5000 cycles per second, which cannot be measured with this equipment. Harmonics of the generator P, however, will be picked up by the radio receiver R, so that if P is set at 1/40 of R or 502 kc, the beat notes work very nicely throughout the system. In other words, when generator P is set on 1/40 the frequency of R to match tuning fork TF, the telephones U connected to A produce a note against a harmonic of the standard 10-kc generator G, which can readily be matched with the note in telephones V and checked up with the frequency meter F, coming within the range of 2000 ± 200 cycles per second. Tuning forks of several frequencies have been used to obtain check values agreeing to the order of one part in 10^6.

For check measurements at 5021 kc, generator P is set in a similar manner. If the same tuning fork is used, a slightly different beat frequency is produced from that at 20,085 kc. In order to make measurements with the above apparatus at a given frequency, the harmonics and beat notes employed must bear certain relations to each other, as are stated below. Let

X = frequency to be measured which is approximately known from frequency assignment.

H = frequency to which generator P is adjusted.

A = audio-frequency note produced after generator P is precisely adjusted in certain relationship to frequency X.

A should have one of the values previously mentioned, i.e., 5–200, 1000 ± 200, 2000 ± 200, etc., cycles per second.

H must have a value such that

(1) A is satisfied.

(2) Beat note between generator P and 10-kc generator G comes in the range preferably from 100 to 2500 cycles per second.

(3) Beat note between harmonic of H and frequency X should come between 400 and 1500 cycles per second in order to be easily matched.

(4) The frequency setting to be preferably under 1000 kc. (Measurements have been made at three times this frequency.)

While the above conditions may seem to be quite formidable, in practice several solutions may be possible. Several measurements are possible by varying (3) using tuning forks of different frequencies.

Data taken on the piezo-controlled transmitting set at NKF upon frequencies of approximately 5021 kc and 20,085 kc gave practically the same results by the above method, although five different conditions as to beat note produced were used. It was of interest to find that measurements made at the Naval Research Laboratory by an entirely different method and in terms of a different standard, agreed with our results within about 2 parts in 10^6.

A consideration of the possibilities of error in the measurements may be of interest. Consider the measurement of 20,085.000 kc. The radio receiver, when properly set, will not introduce an error. If the radio-frequency generator was set at 1/40 the frequency to which the radio receiver was adjusted, it would be set at 502.125 kc. As it cannot be set accurately here, the 40th harmonic of the generator is made to produce a 1000-cycle difference frequency with the incoming signal. If the generator is set low, its frequency will be $502.125-1000/40 = 502.100$ kc. If the thousand-cycle beat note is held to one cycle per second, the generator is set to 1/40 cycle per second, or to 502.100 kc ± 0.025 kc. It is quite difficult, if not impossible, to hold the generator to such precision. If the generator is held so that there is a beat of 1 cycle per second, which is not impossible, the error in setting will be 1 part in 2×10^7. The error in matching the note between the standard and the generator, with the audio-frequency generator, is of considerable importance, because instead of affecting the result by 1/40, it affects it directly. The error in this matching is multiplied by 40 with the frequencies considered. However, it is possible to make the matching quite accurately providing the radio-frequency generator holds, or the matching is carefully made when the 1000-cycle beat note is correct. Changing the setting of a variable air condenser either side of zero beat and taking the mean setting gives a precise adjustment. The setting of the radio-frequency generator affects the ease of this matching by a factor of 50 in this case, because the note which

is matched with the audio-frequency generator is produced by the fundamental frequency (500 kc) of the generator beating with the 50th harmonic of the 10-kc generator. A change of the generator frequency of 1/40 cycle, which represents a change of 1 part in 2×10^7 with respect to the measured frequency, here produces a change of approximately 1 part in 10^5. If referred to the measured frequency this would represent a change of 0.2 kc, which is about five times the difference obtained in measured values for a given day. The factor 50 therefore does not enter appreciably into the calculated error, but has more to do with the difficulties of making the measurement.

The audio-frequency generator output is then determined in terms of the direct reading frequency meter. Errors which may be inherent in this device are likewise multiplied by 40 in arriving at the final result.

In the absence of more data the following estimates of errors in measurement may be listed. The total value thus obtained is of the same order as the departure from the mean values of frequency actually measured.

Estimated error in adjusting generator to receiver	$\pm$ 0.5 part in 10^7
Estimated error in adjusting audio-frequency generator to generator note	$\pm$ 8 part in 10^7
Estimated error in measuring audio-generator note	$\pm$ 4 part in 10^7
Total	$\pm$ 12.5 part in 10^7

As the sign of the errors may be either positive or negative, some of them may tend to cancel others.

The high precision and accuracy of the measurements of station frequencies by the above method arises from the use of harmonics and beat notes plus an acquired skill in the precision of setting the various parts of the equipment. The use of several tuning forks in making the settings verifies the results obtained, and in spite of a large multiplying factor as previously stated, which applies to the errors present, the results usually agree to about 2 parts in 10^6.

Measurements at lower frequencies, such as in the broadcast band, can be made very precisely in the above manner, and have the advantage of a small multiplying factor.

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GRAPHICAL ANALYSIS OF OUTPUT TUBE PERFORMANCE*

By
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Summary—*After outlining the graphical method for the analysis of power tube output as applied to the case of a simple resistive load the method is extended to the case of a plate load presenting a value of resistance that is different for direct current than for alternating current. It is shown that in this case the various load lines cannot be drawn through a common operating point because the effective plate voltage shifts when rectification occurs.*

The method is applied to an experimental pentode and it is shown that in this case the condition for no rectification does not imply the absence of odd or even harmonics.

THE performance of vacuum tubes as amplifiers with relatively small input voltages may be predicted by a consideration of the amplification factor, plate impedance, and mutual conductance. However, in calculating the output of tubes which must deliver power to a loaded circuit of such an amount that use is made of the full capability of the tube, such an assumption cannot be made, because the instantaneous values of mu and r_p are swinging with alternations of plate current and plate voltage.

In this case mathematical analysis becomes very involved. Use, of course, can be made of experimental measurements and this is perhaps the best way to obtain the final answer in such cases. However, the well known graphical method of laying down a load line on the family of static curves representing plate current against plate voltage for various grid potentials is very useful in showing what can be expected. The use of this method requires no elaborate set-up of apparatus and its application can be carried considerably farther than has been done.

The idea in its simplest form may be explained as follows:

Let Fig. 1 represent the static characteristics of an amplifier tube of the triode type such as the 245. If such a tube is connected in a circuit in which the plate load is a pure resistance, the performance may be analyzed by drawing the load line where the lower end of the line represents the value of the plate supply voltage and the slope of the line is established by the value of the load resistance, that is, the resistance is equal to the value of the intercept on the voltage axis divided

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by the value of the intercept on the current axis. The intersection of the load line and the line indicating the plate current for the working

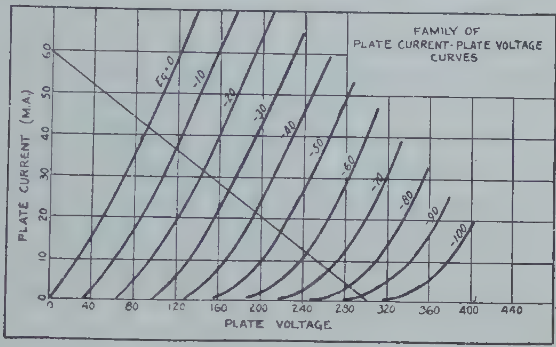

Fig. 1—Typical triode characteristics.

grid voltage represents the operating point of the tube with no input to the grid circuit. The intersection of this line with the family of

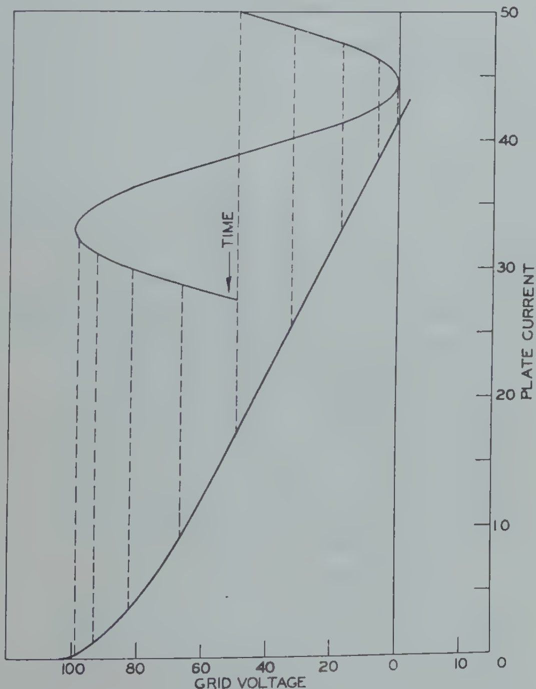

Fig. 2.

curves in effect gives us a graphic solution of two equations, one of which represents the surface defined by the various plate current-plate

voltage curves and the other is the surface represented by the equation of the load line. This solution eliminates plate voltage and we can now draw a plate current grid voltage curve such as Fig. 2.

Assuming a sine wave input we can by the use of Fig. 2 plot the plate current flow through the load resistance against time or the angle of rotation of the vector generating the sine wave. (See Fig. 3) This wave form may be analyzed by the method employing Fourier's series and a determination made of the total power as well as the fundamental and various harmonics. The analysis is simplified considerably by the fact that the first half cycle of the wave form is symmetrical about the 90-deg. axis and the second half cycle about the 270-deg. axis. Due to this fact the sine terms are absent in the solution for

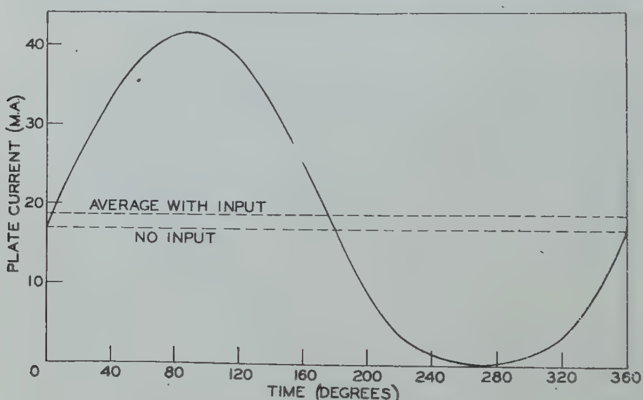

Fig. 3.

the even harmonics, and the cosine terms are absent for the odd harmonics and the value for 20 deg. is the same as that for 160 deg., etc., thus cutting down the arithmetical work considerably. As long as the load is a simple resistance this method of analyzing may be applied to any tube if we can obtain the static characteristics. If the distortion is low so that the output is approximately sinusoidal the power output may be obtained by use of the relation that the output is equal to one-eighth of the product of the voltage swing and the current swing, or

$$P = \frac{(E\ max - E\ min) \times (I\ max - I\ min)}{8}$$

It is comonly stated that the per cent second harmonic is given by the following expression:

$$\text{Per cent } H_2 = \frac{\frac{1}{2}(I\ max + I\ min) - I_0}{(I\ max - I\ min)}$$

This is only a rough approximation and, of course, if the harmonic is large the equation for the power output will be in error.

The graphical method as explained thus far is well known. However, in practice an output tube is not usually loaded with a resistance directly in the plate circuit but is coupled to the load through a transformer or by means of a choke and condenser. In this case the graphical method has frequently been applied erroneously; however, it may be used here to produce results as accurate as those obtained is the case of a pure resistance load. For simplicity we shall assume that a transformer of one-to-one ratio is employed having primary impedance high in comparison with the load resistance and that the only loss in this transformer is due to the d-c resistance of the primary. To direct current, the plate circuit has a resistance equal to that of the primary of the transformer; to alternating current, its impedance in equal to the load resistance. This condition is interpreted in Fig. 4. In this case we have the static characteristics of an experimental pentode but the principles apply as well to any type of tube.

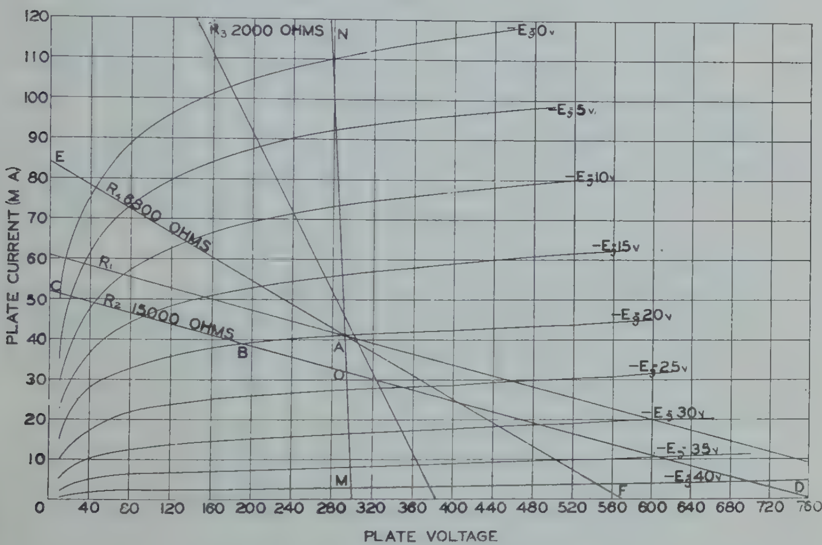

Fig. 4—Typical pentode characteristics.

It is assumed here that we have a 300-volt plate supply. A line MN is drawn having a slope determined by the d-c resistance of the primary, which has been taken as 200 ohms. The lower end of this line rests on the 300-volt point. Assuming a grid bias of -20 volts, line R_1 is drawn through the intersection of the minus 20-volt grid curve and the line OA having a slope determined by the a-c load which has

been taken as 15,000 ohms. If we now assume a grid swing of ± 18 peak volts, draw our output curve and analyze it, we find that we have a steady or d-c component amounting to -4.2 ma. This means that the plate current will not be 42 ma as we have assumed but 37.8 ma. Evidently something is wrong. We must accordingly make a second assumption such as line R_2 which will be parallel to R_1 and cross line OA at a lower value of plate current. If this assumption is correct the average plate current indicated by the point O must equal the value indicated by point B minus the d-c component of the wave as obtained by the analysis of the output curve based on the new line R_2. It may be necessary to make several assumptions before the correct position of the line R_2 can be obtained. However, it is not necessary to analyze the output curve completely or even to draw it; it is merely necessary to average the plate current values for even time intervals for a sine input and ascertain whether or not this average coincides with the assumed average indicated by point O. This point may also be determined by setting up the tube under corresponding operating conditions and determining the d-c plate current with the assumed input.

The decrease in plate current caused by the application of the alternating voltage in the grid circuit has brought about a change in the operating conditions. Since the average plate current has fallen the average plate voltage must rise slightly. This rise is indicated by the difference in plate voltage as indicated by the points A and O. However, the effective plate voltage as far as the generation of an alternating voltage across the a-c plate load is concerned has shifted from point A to point B or has fallen from 292 volts to 220 volts. Point B represents the instantaneous value of plate voltage and plate current when the instantaneous value of the applied grid voltage is zero. Point O represents the average value of plate current and voltage.

Line R_3 shows the conditions which obtain for a load of 2000 ohms. Note that the effective plate voltage has increased slightly in this case. Under the conditions shown, that is, where the a-c plate load is of higher resistance than the d-c plate load, negative rectification produces a drop in effective plate voltage and positive rectification a rise. If the a-c plate load were of lower value than the d-c load the sign of the change would be reversed. Such a condition is found in detector tubes with a resistive plate load and a radio-frequency by-pass condenser.

The change in operating point is, of course, not instantaneous but a short period of time will elapse between the application of the alternating voltage and the arrival at the steady state. This is perhaps more

easily understood in the case where a large choke is used directly in the plate circuit and is coupled to the load through a condenser. Roughly, the alternating component of the plate current will flow through the resistor and the direct component through the choke. The transient condition will persist until the field of the choke changes sufficiently to accomodate the new value of plate current. The conditions with transformer coupling are closely equivalent.

If there is no rectification the load line will be drawn through point A. For 6800 ohms, rectification is negligible and the line R_4 passes through A. For loads of less than this value the effective working voltage is slightly higher and for loads of greater resistance the effective plate voltage drops.

The error which arises due to drawing all load lines through a single point such as A is not large if the rectification is small. However, in the case of the 15,000-ohm load the results were as indicated in the table. (The values for a load of 2000 ohms and 6800 ohms have also been included.)

TABLE I

Load Line	Load Ohms	DC MA	Output Watts	Per Cent Total Voltage Distortion			
				2nd H	3rd H	4th H	5th H
R_1	15,000	−4.2	5.85	12.8	10.0	1.9	1.6
R_2	15,000	−6.4	4.43	20.6	7.2	4.2	0.9
R_3	2,000	4.9	2.25	10.8	2.3	0.1	0.2
R_4	6,800	0.0	4.78		6.3		

Since low resistances give positive rectification and high resistances negative rectification there must be some value of load which will not produce any change in plate current for the particular alternating grid voltage in question. The condition for no rectification does not necessarily mean no harmonics although it is probable that the even harmonics will be of low value. Because of the fact that the upper half of the output wave-form is symmetrical about the 90-deg. axis and the lower half about the 270-deg. axis, the expression for the instantaneous value of the alternating plate current may be written, considering current at point B as zero.

$$i = a_0 + c_1 \sin\theta + c_2 \sin(2\theta + \pi/2) + c_3 \sin 3\theta + c_4 \sin(4\theta + \pi/2) + \cdots\cdots.$$

at point B, θ is zero, i is zero, the odd sine terms are zero and the even sine terms are equal to unity, therefore, the expression reduces to

$$a_0 + c_2 + c_4 + \cdots\cdots = 0.$$

This gives an interesting check on the accuracy of the analysis. If there is no rectification, the three points A, O, and B will coalesce, or

$$a_0 = 0 \text{ and } c_2 + c_4 + \cdots\cdots = 0.$$

The algebraic sum of all the even coefficients must be zero. There is then a possibility that at the point of no rectification there may be substantial amounts of even harmonics; however, in all the cases investigated the even harmonics were very low at this point, so that the limitations of the accuracy of the method precluded a positive check on the last equation. However, in several cases measured harmonic analyses bore out these conclusions.

In the analysis of the pentode as enumerated in the table it will be noted that for a load of 6800 ohms the second and fourth harmonics were negligible. The lack of rectification does not rule out the odd

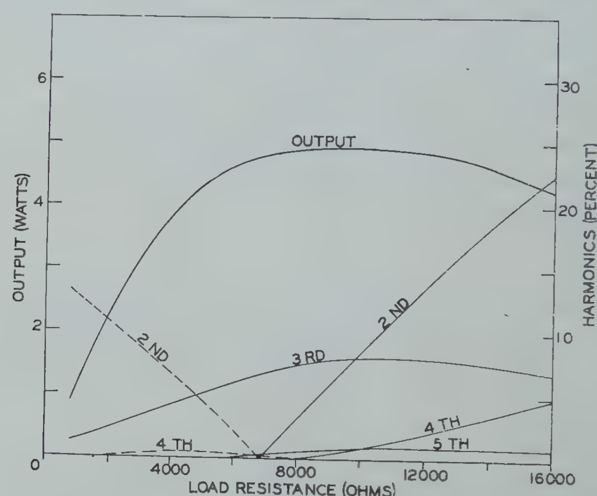

Fig. 5—Power output and per cent harmonics for maximum grid swing of experimental pentode.

harmonics which may be present in force. Power pentodes show considerable third harmonic when the load resistance is adjusted for zero rectification, many of them showing over ten per cent. The lack of rectification means that the crowding on the lower extreme of the swing is offset by crowding on the upper end due to encountering the region of the knees in the curves. Such symmetrical crowding indicates the presence of odd harmonics.

Fig. 5 shows the power output and the voltage per cent for the first four partials for the same input and working conditions as reported in Fig. 4. The dotted lines indicate a negative coefficient for the harmonic. Fig. 6 shows the output for a 245 tube represented in the same way as Fig. 5. It will be noted that for the 245 the maximum power was obtained when the load resistance was approximately equal to the internal plate resistance. However, with the pentode this was

not the case but the maximum output was obtained at approximately a 10,000-ohm load.

Whenever the working range does not reach out into the nonuniformly spaced or the curved portions of the static characteristic curves the maximum output will be obtained when the slope of the load line equals minus the slope of the plate current curve. This is merely another way of stating the old proposition that maximum power is obtained when the load resistance equals the internal resistance of the generator.

However, when the input voltage is such that the working range extends into the nonlinear portion of the characteristics the value of the load for maximum power will change. In the case of the triode as

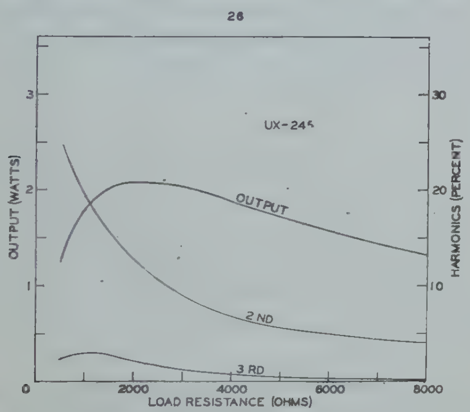

Fig. 6—Power output and per cent harmonics for maximun grid swing of power triode.

typified by Fig. 1, it is apparent that the slope of the load line for optimum power will be less than that of the tube characteristics or that the load resistance will be greater than the tube resistance. When distortion is considered it is even more important to keep out of the curved portion of the characteristics which means a still further increase in the load resistance or a flatter slope for the load line.

Pentode characteristics show curvature of an opposite sign. In this case in order to avoid distortion and to get optimum power it is necessary to make the load line steeper than the slope of the plate current line at the working point. Here odd harmonics are a minimum for zero load but even harmonics are negligible for a definite load resistance, increasing for loads on either side of this particular value. All this brings out the point that there is no definite ratio between optimum load resistance and internal tube resistance but that this ratio will depend upon the characteristics of the tube and the working

point assumed. If the plate voltage as represented in both Figs. 1 and 4 could be materially increased without danger to the tube, analysis would show that the optimum plate load in each case would more nearly approach that of the tube resistance.

The fact that the internal plate resistance of the tube is not a constant accounts for the apparent breakdown of the law that load resistance must equal generator resistance for maximum power output. In Fig. 4 plate resistance is indicated by the slope of the plate current plate voltage curves. With a large grid swing and a load resistance of 6800 ohms it is evident that the instantaneous value of the reciprocal of r_p must change from that indicated by the slope of the characteristic at point E to that indicated by the slope at point F. It is difficult to say just what the effective plate impedance is under these circumstances. However, the exact nature of the tube output can be determined by the graphic method as has been outlined.

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THE ROLE OF RADIO IN GROWTH OF INTERNATIONAL COMMUNICATION*

By

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INTERNATIONAL communication in some form has existed since the beginning of civilization, while the development of rapid communication as we know it today has occurred wholly within the last hundred years, an interval of time exceedingly small compared to the age of civilization. The development of radio has been even more rapid than that of other forms of communication, and the greatest progress of radio may be said to have occurred since the beginning of the world war.

The development of communication in its international aspects may be considered closely allied to the development of communication itself. That radio is no respecter of national boundaries is only too well known. The phenomenal growth of radio communication has given rise to considerable misgiving in the minds of many as to the rôle which radio is to play in the future of communication. Radio has come to be a byword well known to millions through the development of radio broadcasting. In the popular imagination, it is felt that it is only a question of time until radio will become the universal medium for communication, and that wires and cables, becoming obsolete, will be abandoned. On the other hand, there are those who believe that the future of radio is exceedingly limited, and will be confined largely to broadcasting and communication with, and between, mobile stations where, of course, the use of wires would be impossible. It is believed by some that radio will be displaced eventually from the broadcast field for local areas, by the use of wire broadcast systems. There are even those who believe that the wire interests are making a concerted effort to gain control of radio in order to stifle its growth and to overcome the menace of radio to the wire communication systems of the world. It is quite evident to us all that these extremely divergent views are neither founded upon logic nor upon a clear understanding of the technical and economic problems involved in communication in general.

A little consideration will show that in the future development of

* Decimal classification R450. Original manuscript received by the Institute, August 2, 1930. Presented before Fifth Annual Convention of the Institute, Toronto, Ont., Canada, August 19, 1930.

international communication there will be a very definite and logical use for both wire and radio communications. We might mention briefly some of the principal factors which govern this situation. It is well known that short-wave radio stations for long-distance communication, at least with a volume of traffic not too great, require a smaller investment than the corresponding cable or wire systems. This is particularly noteworthy in the case of long-distance transoceanic communications. On the other hand, between important widely separated centers, where the traffic density is great, or where there is important way traffic to be picked up, it is probably true that wire systems can operate more economically than radio systems, and that the cost per unit of communication is lower than corresponding radio costs. The development of both wire and radio for transoceanic telegraph work has proceeded to a point where one may estimate with considerable exactness the cost of each facility and thus determine in advance the relative advantages of each for given conditions and traffic load. As radio circuits are subject to interruptions from time to time from atmospheric interference or magnetic storms, continuity of service over a full 24-hour period is not always assured. While radio circuits do suffer interruptions of relatively short duration intermittently, it is also known that important cable circuits have been interrupted by natural causes and remained inoperative over long periods of time. Radio possesses the distinct advantage of being able to transmit to several places at once, or to widely separated localities at different hours, while cable traffic must be confined to the cable route and its corresponding lines. The use of radio avoids the difficulty inherent in connecting the shore end of a cable with interior points, and also the objection voiced by certain inland countries when their international communications pass through the facilities of another country, subject at times to censorship. The inherent secrecy of cable communication is of particular importance in time of war, while radio communication does not possess in itself the same degree of secrecy as the cables, and may be subjected to artificial interference by the enemy. On the other hand, cables can, and have been, cut by military agencies, and have remained inoperative during the entire period of war. It seems evident from the obvious advantages and corresponding disadvantages of each, that neither will displace the other, and that we must look in the future toward a coördination of the radio and cable systems where each will take a predominating position in the particular economic field which it is best suited to serve. Radio and cable services are essentially complementary.

The fact, not universally recognized, that the number of radio

channels available, particularly those for use over long distances, is limited, will serve to confine the use of radio more and more in the future to those services for which it is best adapted. Those services where radio is essential, such as broadcasting, transoceanic telephony, marine and aeronautical communication and direction finding services, television, and meteorological service, must not be deprived of adequate radio channels in order to build up nonessential radio circuits, but on the other hand, should be allowed to obtain their fullest development by freely allocating to these services the radio channels essential to their progress in the future. The extension of wire and cable communication systems to localities not formerly served on account of economic factors, will from time to time release valuable radio channels for the development and pioneering of new services where the use of radio is essential.

In certain circles, an erroneous impression is in existence that the recent spectacular development of radio has brought about an extraordinary competitive situation between wire and radio services, particularly in the international field. If one surveys the great opportunity throughout the world for the improvement of existing communication facilities and the necessity for building up facilities where they do not exist at present, one finds unlimited opportunity for the expansion of both wire and radio systems. It is obvious that the development of either radio or wire traffic in new areas must add to the business handled by its complementary facility. Authorities agree that there exists a very real need in many fields for further advancing and increasing international communications.

After a study of the pressing communication problem confronting Great Britain and the British Dominions, through the uneconomic parallel competitive construction of radio and cable facilities, each without due regard for the other, it was found necessary to provide a means for their coördinated operation and harmonious development in order to safeguard the future of electrical communications in the British Empire.

It seems evident that any agency or company engaged in communication upon an international scale, must employ both wire and radio in order to take advantage of the varying conditions which must be met in order to render a complete service. It is not by means of unnatural competition that the public will receive the improvements in communications and lower rates in the future, but on the other hand, it is only by the closest coöperation between wire and radio systems that satisfactory results will be obtained. The phenomenal progress and growth in international communications in recent years have been

due in no small degree to the systematic manner in which research and engineering study have been organized and carried out by the communication interests. Progress in the future may be assured only by continuation of the broad-minded policies which have proved so successful in the past.

In order to justify these policies, the communication interest must have reasonable assurance that they will be permitted to work out international communication problems along economic lines, free from artificial restrictions which foster wasteful competition with its attendant losses in revenues and ultimate deterioration of the communication services themselves.

The development of telephony upon an international scale has been somewhat slower than the growth of international telegraphy, due to the language difficulty involved, not to mention the difficult technical problem involved in the coördination of telephone systems operated by different agencies and administrations. The obvious advantages inherent in unity of administration and language made possible the early development of long distance telephony in the United States. The progress made toward the solution of the technical problems of long-distance telephony in the United States, and the ensuing rapid expansion of long-distance telephone circuits, indicated to the European nations that the means for telephone communication on a truly international scale were already at hand. Splendid progress having been made in recent years by the various European administrations and agencies in building up a network of international telephone lines, it was only a further step in this rapidly moving development to seek means to overcome the natural barriers preventing intercommunication between the telephone networks of the new and old world. The difficulties to be overcome in bridging the ocean gap were many, but fortunately the development of radio had reached a point where successful communication on a commercial scale between Europe and America was accomplished after a period of intensive study and research. The faith of those who sponsored the work of pioneering telephone communication paths across the Atlantic was justified almost immediately, by the rapid growth of traffic from less than ten messages per day in 1927 to nearly fifty per day in 1929.

The marked success of the pioneer radiotelephone circuit connecting Europe and America was followed by intensive activity in the construction of other radio circuits between the important telephone areas of the world. The next important step toward the ultimate accomplishment of international telephony upon a world-wide basis, was the construction of radiotelephone circuits connecting the tele-

Fig. 1.—The New York-London link consists of four circuits in operation and one under construction.

phone system of Spain to the wire networks in Argentina, Chile, and Uruguay. This was followed by the construction of a radiotelephone circuit linking North America and the three above-mentioned South American countries. As radiotelegraphy had already been applied by various European nations having colonial interests, it was natural for them to utilize short-wave radiotelephony to bring their colonies into even closer contact with the mother country. The rapidity with which radiotelephone circuits have been established within the last three

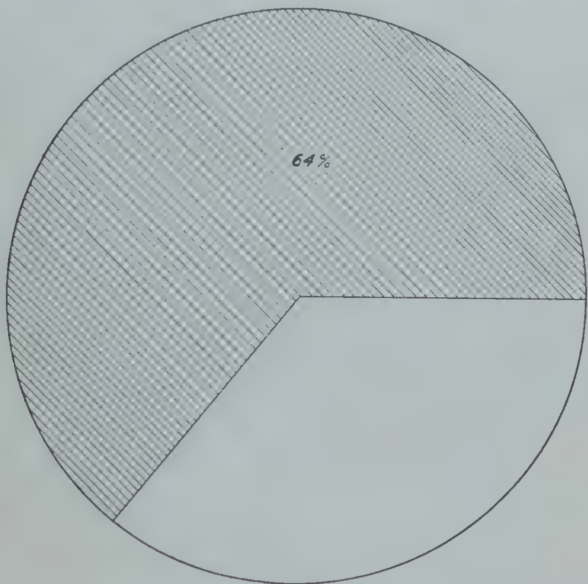

Fig. 2—Interconnecting telephones, 1926. The shaded area represents the telephones of the United States, Canada, and Cuba which were intercommunicating in 1926—64 per cent of the world's telephones.

years is quite remarkable. Fig. 1 indicates the extent of radiotelephone development in operation or projected for operation in the near future. It is interesting to note that during the last three years 80,000 miles of radiotelephone circuit have been placed in operation, and an additional 90,000 circuit miles are scheduled for operation by the end of 1931. The relative importance of these new and projected circuits is, of course, determined by the density of traffic handled, and the extent of the telephone development connected to the radio terminal stations.

The technical developments in the art of electrical communication have already proceeded to the point where it is theoretically possible for any individual situated at any place on the globe to communicate by telephone with any other individual at any other place by means of

a combination of wire and radio circuits. The relative extent to which these technical possibilities have already been reached in a commercial sense is indicated by Fig. 3, which shows graphically out of a total world development of 35,000,000 telephones, 30,000,000 telephones may be interconnected by virtue of utilization of the various continental land wire networks and their interconnecting radio links. Fig. 2 shows the greatest extent of interconnected telephone development prior to the advent of radiotelephony on an international scale. The

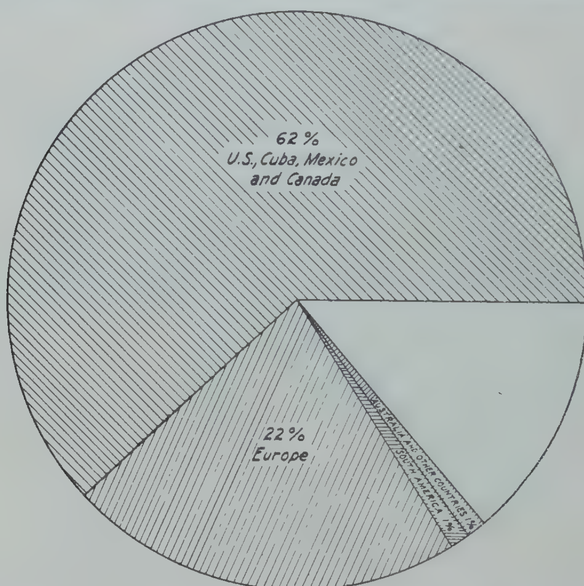

Fig. 3—Interconnecting telephones, 1930. The shaded area represents the intercommunicating telephones of the world—86 per cent of the total—consisting of intercommunicating groups connected together into one large group by radio links.

greatest use of radio by the greatest number as a means of direct communication from person to person, either by record or the spoken word, can be developed only by a thorough coördination with existing and future wire systems.

It is agreed that the development of communication fosters a community of interest and a community of interest in turn requires further development of communications, and so on, in an ever widening circle. In the light of the above, i⁺ is not remarkable, that radiotelephone communication between Europe and the Americas having reached a position of commercial importance, a further demand arose for telephone communication with large passenger ships plying between the principal world ports. Again it was found that short-wave radio

was admirably qualified in many respects for a radiotelephone service between oceangoing ships and the telephone networks on either shore. It is now possible for travelers in three British ships and one American ship to carry on a telephone conversation with a large percentage of the world's telephones during the voyage.

Radio is destined to play an important part in the development of new international transportation systems by its aid to the safety of navigation of airplanes and airships in transoceanic and transcontinental flights. Radio has contributed in no small measure to the success already achieved by this new means of travel. The accomplishment of the only wholly successful transatlantic flight from east to west was attributed in a large degree to the invaluable assistance of radio during the flight.

It is to radio that we must look in the future for the greatest development of television upon a commercial scale, as the wide frequency bands required for television that is worthy of the name, can only be made available economically in the lower range of the short-wave spectrum.

Prior to the war, the international aspect of radio communication was of negligible importance, international interest being chiefly concerned with the use of radio for the safeguarding of life at sea. International rules and regulations governing the use of radio were quite simple in character, and agreement was readily obtained. However, in recent years, the use of radio internationally has become more and more important, and it was universally recognized that its development would be seriously hampered unless wise provisions governing the use of radio could be formulated and agreed upon universally. The International Radio Conference called at Washington in 1927, largely attended by representatives of the principal nations of the world, did important work in formulating rules tending toward the most efficient use of radio and the prevention of international interference. It was recognized before the Washington Conference was called, that the task confronting the delegates was so great and of such importance that it would be impossible to hope for its accomplishment within a reasonable time. It was also felt that the art of short-wave radio was so new that it would be dangerously restrictive to attempt to formulate other than the most basic rules for the use of the frequencies in the high-frequency region of the radio spectrum until further experience had been gained internationally in their use. It was also agreed that the advent of short-wave radio had brought the international aspect of radio to the fore to such an important degree that it would be very desirable in order to foster the uninterrupted

development of radio, to provide for an international consulting body to study important technical aspects of short-wave radio. It was agreed that the success of wire telephony upon an international scale in Europe was due in no small measure to the fine coöperation and intensive effort of the Comité Consultatif Internationale (Telephone) and that a similar international body could profitably be constituted to study and recommend to the nations important technical aspects of radio. This committee, the Comité Consultatif Internationale de Radio, met last year at the Hague, where a number of problems of importance to the future growth of radio were studied. Much work yet remains to be done. It has been found necessary to convene the Comité Consultatif Internationale de Radio next year at Copenhagen, in order to prepare the way for the next International Radio Conference which is scheduled to meet in 1932 in Madrid.

The future growth of radio is largely dependent upon the formulation of wise technical and administrative rules governing its use. The spirit manifested in the International Radio Conferences has been one of unlimited confidence in the future of radio in international communication. This bright future can only be realized if a minimum of restrictions be placed upon the use of radio and only such legislation should be formulated that has proved by the test of time to be constructive and not tending toward restriction in any sense of the word. As it is of the greatest importance that radio be allowed to develop unhampered by technical restrictions, so it is equally vital that communications in general be free from artificial restrictions in order to attain their fullest development in accordance with economic law.

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POWER EQUIPMENT FOR AIRCRAFT RADIO TRANSMITTERS*

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Summary—*This paper covers all of the systems of power equipment now used or contemplated for supplying power to aircraft radio transmitters. The various types of power equipment are described and the advantages and disadvantages of each type are discussed.*

The types of power equipment discussed are (1) the wind driven generator, (2) the dynamotor, (3) the main engine driven generator, (4) the auxiliary engine generator set, (5) the combination wind driven generator and dynamotor, and (6) the constant speed main engine driven alternator.

One of the major problems in the application of radio to aircraft is that of securing electrical power for operating the transmitter. It is the purpose of this paper to describe the various methods used for generating electrical power on airplanes and to discuss the advantages and disadvantages of each method. The discussion will be limited to the systems of power equipment which are suitable for commercial aviation and no attempt will be made to cover the special problems of military aviation.

The principal problems confronting the designer of power equipment for commercial aircraft are (1) to supply the power required to operate the transmitter and to charge the ship's twelve-volt storage battery, (2) to provide, if possible, power for the transmitter even when the main power plant of the airplane is crippled, (3) to provide the maximum degree of reliability, (4) to design the equipment so that a minimum amount of maintenance is required, and (5) to accomplish these various results with the minimum possible decrease in pay load.

The five factors to be considered are, therefore, electrical performance, emergency operation, reliability, maintenance, and economy. For any particular type of power equipment it is necessary to select a compromise of the four factors of performance, reliability, maintenance, and economy. It is not the purpose of this paper to go into each type of power equipment in sufficient detail to show how a definite balance of these factors is selected for a given type of power equipment, but rather to show how these factors will vary as the type of power equipment itself is changed.

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The amount of electrical power which will be required will vary with the size and design of the transmitter, and will also depend to some extent upon the amount of power required for lights, starting equipment, and other accessories. Most transport planes have an electrical power requirement of 700 watts and this rating has been chosen as the basis of comparison for the various types of power equipment.

A radio transmitter requires power in the form of direct current at a variety of voltages. As a rule only the two principal voltages are generated, a comparatively low voltage for the filaments of the tubes and for charging the storage battery, and a much higher voltage for the maximum plate potential required.

For 700-watt equipment the usual rating is 300 watts at 14.6 volts and 400 watts at 1050 volts. The high tension output is divided by means of a potentiometer system to give the various plate and grid potentials required. The low tension output is fed to the 12-volt storage battery and thence to the filaments of the radio tubes and to the various accessories requiring electrical power. The high tension and low tension currents may be supplied from the same machine or from different machines.

The electrical requirements for a transmitter power supply are that (1) the filament and plate circuits must be electrically insulated from each other, (2) the voltage supplied the filaments of the tubes must be maintained within five per cent of the rated filament voltage for all flying speeds and for all values of high voltage output that may be encountered, and (3) the plate voltage must be practically independent of flying speed. It is also desirable that the load regulation of the plate voltage be as good as possible, especially for transmitters requiring a variable high tension load and that both the filament voltage and the plate voltage be free from irregularities such as will modulate the output of the transmitter.

We have stated that for a 700-watt installation the high tension voltage would probably be 1050 volts, but voltages as high as 2000 volts have been used for aircraft transmitters in this country and even higher voltages for some European transmitters. There are two distinct methods which may be used for obtaining high voltage direct current. The simplest method and the method most commonly used for voltages up to about 1200 volts is to generate the required voltage directly. The principal drawback to this method is that it is difficult to make a small, reliable, high voltage, direct-current generator. Part of the difficulty lies in the fact that extremely small wire must be used for winding the armature, and part of it in the fact that very little

space is available for insulation and for creepage surfaces. The difficulty of building a direct-current machine increases rapidly with the voltage and a 2000-volt generator will be about twice as heavy as a 1000-volt generator of the same rating. A final objection to this type of machine is that a heavily insulated cable is necessary for carrying the high voltage from the generating equipment to the transmitter. The cable represents a considerable proportion of the total weight of the generating equipment in many instances. Also, high voltage wiring on an airplane constitutes an appreciable danger to the passengers and crew.

The development of the highly efficient mercury vapor rectifier tube has made possible a second method of obtaining high voltage direct current. Alternating current is first generated at a comparatively high frequency such as from 400 to 1000 cycles. Any convenient value of voltage can be generated. A transformer is used to give any desired high tension voltage and the high tension alternating current is then rectified and filtered. There are several reasons for the use of as high a frequency as is practical. The weights of the transformer and filter are almost inversely proportional to the frequency used. A generator of the inductor type can be used and such a generator is smaller in size, lighter in weight, and higher in efficiency than the conventional type of alternator. It can also be constructed to be self-excited and to supply battery charging current.

A low voltage alternator is fundamentally much more reliable than a high voltage direct-current machine. For most ratings the weight of the total equipment necessary for the rectified alternating-current system will be practically the same as that required for the high voltage generator alone. For very high voltages in proportion to the size of the machine the alternating-current system will give the lesser weight. This is of interest in connection with the increasing use of high impedance screen-grid tubes which require higher plate voltages than three-element tubes of similar rating. The over-all efficiency of the two systems will be very nearly identical. The alternating-current system does not require the airplane to be wired with cables carrying dangerous potentials since the transformer, filter, and rectifier are the only high voltage units used and these may be kept within the transmitter assembly.

The chief disadvantage of the alternating-current system is that the load regulation is poor. This is due to the fact that when there is no load on the system the filter condensers become charged to the peak voltage of the alternating-current wave and this voltage cannot be maintained when any current is flowing. For telephone transmitters

poor load regulation is not especially objectionable since the power equipment operates at practically a constant load.

With any system of generating equipment it is of course necessary to have a primary source of power. The electrical performance that can be obtained will depend upon the limitations of the primary source of power and also upon the extent to which these limitations can be overcome in the design of the equipment. The usual primary source of power on airplanes at present is the main engine (or engines) of the airplane. The ship's storage battery might also be regarded as a primary source of power of very limited time rating as it would be possible to use a battery for all electrical power purposes and to charge the battery between flights much as the main engine is refueled between flights. In all but one system of power equipment having an emergency rating the battery supplies the power for emergency operation. A battery of sufficient capacity to serve as a sole source of power, however, would be far too heavy to be practical. The only source of power other than the main engine which appears to be at all practical is a small auxiliary gasoline engine. Such an engine has the advantage that it will provide full time emergency power as long as any fuel is available.

The characteristics of the main engine are not very suitable for a generator drive. The voltage generated by any given machine depends upon the product of the speed and the field strength. Since the speed of the main engine is variable it is necessary to use some sort of regulating device to secure constant voltage. There are two ways in which this can be done. The first method requires a regulated mechanical drive between the engine and the generator so that the speed of the generator is substantially independent of the speed of the engine over the operating range of engine speeds. An example of this method is the wind driven generator driven by means of the constant speed, self-regulating propeller. The second method allows the generator speed to vary in proportion to the engine speed and makes use of a voltage regulator to adjust the field strength of the generator to the suitable value for any given speed and load.

An important distinction between these two methods of generator drive is that a constant speed generator may be used for either alternating or direct current, whereas the variable speed generator can be used for direct current only with any type of generators now available.

Operating economy is of considerable importance to commercial aviation, although it is seldom that power equipment can be selected entirely on the basis of economy. The important factor in operating economy is the decrease in pay load made necessary by the weight of

the power equipment and by the power required from the engine to operate the equipment. The decrease in pay load will be termed the effective weight of the power equipment.

In order to derive comparative figures for effective weight it will be necessary to assume the same operating conditions for all types of equipment. Therefore, it will be assumed that each type of equipment is used on a plane flying at a cruising speed of 100 miles per hour with no change in altitude. The customary assumption will be made that the propeller efficiency is 75 per cent. There is some question as to the most representative value of lift-to-drag ratio to assume, but for the other conditions assumed a ratio of 7 to 1 should be close enough for our purposes. This ratio will not remain strictly constant but the change will be so slight that it can be neglected.

If no power is taken from the engine to operate the generating equipment the pay load will have to be decreased by the actual weight of the equipment in order to maintain the given flying conditions when the generating equipment is added. If power is required from the engine to operate the generating equipment there must be a further decrease in pay load. This decrease in pay load caused by power taken from the main engine is known as the equivalent weight of the equipment. The total decrease in pay load is, therefore, the sum of the actual and equivalent weights of the power equipment.

Under the conditions which have been assumed each pound of weight requires an output from the main engine of

$$\frac{1\times 100}{7\times 0.75\times 375}=0.0508 \text{ hp. or } 38 \text{ watts}$$

Conversely, an output of one kilowatt from the main engine will be equivalent to a weight of 26.3 pounds.

There is one other factor involved in considerations of economy. This is the fact that the equipment may not represent the weight of a passenger, but may occupy space which would otherwise be available for one. Some types of power equipment do not require any cargo space at all and whether or not other types require cargo space depends upon the layout of the plane. As yet it is not the custom to design airplanes with the requirements of the radio equipment in mind and the radio equipment must be fitted in after the airplane is completed.

We are now ready to take up the various types of power equipment in detail. The weights which will be used are either weights of existing apparatus, or weights determined by very minor alterations of existing apparatus. They are weights which can be obtained for machines of

good reliability and are in every case as low as appears to be practical in the present state of the art. Weights are, of course, being continually reduced as improvements are made in design and as more suitable materials become available, but in general such reductions in weight will apply more or less equally to all types of equipment and will not affect our comparisons greatly.

The Wind Driven Generator

The first system to be considered will be that using a wind driven generator mounted in the slip stream and driven by means of a propeller. Wind driven generators were first used for securing power for aircraft radio equipment during the late war. The original wind driven generators were driven by means of a constant pitch wooden propeller. Various unsatisfactory types of voltage regulators were used or else the voltage was allowed to vary with the speed. Spark transmitters were used at that time and considerable variation in voltage was allowable. Because of the military necessity performance was acceptable which would not be tolerated for commercial service.

The modern wind driven generator owes its advantages largely to the self-regulating propeller which does away with the necessity of an electrical voltage regulator. A variable pitch propeller is used with a built-in centrifugal mechanism which adjusts the pitch of the propeller to maintain very nearly constant speed with changes in slip stream velocity, generator load, or both. The wind driven generator with the self-regulating propeller is the only form of constant speed generator obtaining power from the main engine which is at present commercially available. Because of the excellent speed regulation either direct-current or alternating-current generators can be used.

Tests have shown that the temperature rise of a wind driven generator in flight is of the order of one-fourth of the temperature rise for the same output on a bench test. This is a result of the excellent cooling obtained from the slip stream. As a consequence of this cooling the wind driven generator can be designed to have a very high output per pound.

The housing of a wind driven generator must be streamlined as completely as possible to keep parasitic drag at a minimum value. The generator must, of course, be entirely weatherproof. It must have a low value of starting torque or the propeller will not pick up. A tough, fatigue resisting shaft is necessary to withstand the vibration and bending moment of the propeller. Ball bearings are, of course, necessary because of the thrust of the propeller and also to permit operation in any position. Where possible, lightweight materials are

used, but iron and copper must be used for the magnetic and electrical parts. Contrary to the opinion of some people the use of aluminum for a conductor instead of copper would make the generator much heavier in weight instead of lighter. The reason for this is that the copper will comprise but about twenty per cent of the total weight of the machine and the use of a bulky material like aluminum will greatly increase the size and weight of the heavier portions of the machine.

The most striking feature in the electrical design of a wind driven generator is the compact field structure and large armature. These proportions are possible because of the ventilation of the frame of the machine and make possible the excellent performance of weight efficiency of the wind driven generator.

The usual form of wind driven generator does not provide any emergency rating at all, except that the generator may be operated while a crippled airplane is gliding to a landing if the gliding speed is high enough to operate the equipment. A new development in wind driven generators which will provide some emergency communication at the expense of considerable added weight will be discussed later.

In discussing reliability it is necessary to make a distinction between the direct-current wind driven generator and the alternating-current wind driven generator, but this same distinction will hold for any type of power equipment. While the direct-current wind driven generator can be made fairly troubleproof by careful design and testing, there is no doubt but that the alternating-current machine is fundamentally much more reliable. Where voltages of the order of a thousand volts are involved a small amount of dirt such as carbon dust from the brushes may form a path for leakage current and eventually break down the insulation and cause a complete failure of the machine.

With the alternating-current system there is comparatively little danger of failure. The low voltage alternator is simple and rugged. A high voltage transformer is comparatively easy to build and test and should be entirely reliable. Rectifier tubes are easily replaceable and in any case are usually used in pairs so that a complete failure is not likely to occur. Filter condensers can be fused so that a shorted condenser will be cut out of the circuit.

The self-regulating propellers are considered to be fairly reliable although they occasionally get out of adjustment. Even if they are out of adjustment they will usually operate the generator after a fashion so that a complete breakdown of communication is not likely to occur from this cause.

The wind driven generator requires only such maintenance as

would be given any generator except that it should be inspected frequently.

To calculate the decrease in pay load caused by a wind driven generator under the conditions previously assumed it is necessary to know the efficiency of the self-regulating propeller. Very little experimental data are available concerning this factor, although the manufacturers of the Deslaurier's self-regulating propeller have published a pamphlet giving the results of a wind tunnel test on a wind driven generator at somewhat less load than we are considering. From the results of this test it seems reasonable to assume that approximately 70 per cent of the power taken from the slip stream is delivered to the generator shaft at the air speed and propeller load we have assumed. This factor includes all of the losses due to parasitic drag on the generator and its mounting. The Deslaurier tests indicate that the efficiency of the propeller falls off considerably with increasing speed and may be as low as 40 per cent at 150 miles per hour.

The efficiency of a 700-watt direct-current generator will be approximately 60 per cent. A self-excited inductor alternator may have an efficiency as high as 80 per cent, but the losses in the transformer and rectifier will bring the over-all efficiency down to approximately the same value as that of the direct-current generator or 60 per cent.

The power required from the engine directly will be

$$\frac{700}{0.75\times 0.70\times 0.60}=2215 \text{ watts.}$$

The equivalent weight will be 2215/38 = 58 pounds. The decrease in pay load or the effective weight is as follows:

	Direct Current	800-Cycle Alternating Current
Generator	28 lb.	16 lb.
Propeller	5.5	5.5
38 amp-hr. battery	36	36
Battery relay	2	2
Rectifier unit		10
Cables	6*	3*
Actual weight	77.5	72.5
Equivalent weight	58.0	58.0
Effective weight	135.5	130.5

* Estimated values.

The advantages of the wind driven generator are:

1. Good voltage regulation is secured without a voltage regulator.
2. Either direct- or alternating-current generators can be used.
3. The wind driven generator is adaptable to any airplane.
4. Good reliability is secured.
5. Very little maintenance is required.
6. The generator is ventilated automatically.
7. The wind driven generator does not require any cargo space.
8. A failure of the generating equipment cannot put the main engine out of commission.

The disadvantages are:

1. The wind driven generator does not have any emergency rating.
2. The efficiency of power conversion is low.
3. There is some possibility of injury from the propeller.

The Dynamotor

It is commonly believed that the wind driven generator offers a very high head resistance in spite of the fact that such experimental evidence as is available indicates that this is not the case. This belief, together with the need for emergency operation has led to the development of the dynamotor system. This system is used extensively by the leading commercial lines although it is not very economical.

Emergency operation is secured by making it possible to obtain both filament power and plate power from the battery. A large and heavy battery is necessary since the total drain on the battery will be about 70 amperes for radio equipment such as would be used with a 700-watt power system. Considerable difficulty has been experienced in maintaining batteries in a fully charged state under operating conditions and even a fully charged battery will not operate the equipment for any great length of time.

Both alternating- and direct-current dynamotors are in use, although alternating-current dynamotors have not yet been used for power systems requiring as much as 400 watts of high tension current. No particular description of the direct-current dynamotor will be required since this type of machine is very similar to a double voltage direct-current generator. The chief difference is that the ratio of the terminal voltages of the two windings differs from the turn ratio by the sum of the IR drops in the two windings instead of by the difference of the IR drops in the windings as is the case with the double voltage generator. This, incidentally, is the reason an ordinary wind driven generator cannot be used as a dynamotor for emergency operation.

An inverted rotary converter could be used to generate alternating current, but such a machine would not be very practical, because of the low voltage and because the frequency would be too low for a lightweight transformer and filter. An inductor dynamotor on the other hand is light in weight, gives high-frequency alternating current, and is fairly efficient. It does not have particularly good speed regulation and the voltage regulation is usually about 30 per cent. When this regulation is added to the voltage regulation of the filter it will be seen that this type of machine is more practical for telphone work than for telegraph work where the load is varied every time that the key is depressed. Since the rectifier tube filaments have to be operated from the alternating current, special compensating devices are required to hold the voltage on these filaments within allowable limits when the load is variable.

It is, of course, necessary to provide some means of charging the storage battery. This is usually accomplished by means of a low voltage generator coupled directly to the engine. The generator requires a voltage regulator because of the varying engine speed.

The performance of the dynamotor system is good, although the voltage regulation is inferior to that of a wind driven generator. The battery absorbs most of the electrical disturbances caused by the vibrating contacts of the voltage regulator and in addition insures a steady voltage for the tube filaments.

Nearly all dyanomotors are totally enclosed to avoid any possible fire hazard from sparking at the brushes in case there are gas fumes in the airplane. An intermittent temperature rating is usually sufficient and makes it possible to save considerable weight in designing the dynamotor.

A 70-pound battery, if fully charged, will operate a 400-watt dynamotor for about thirty minutes for emergency communication. The battery voltage, and consequently the high tension voltage will decrease considerably towards the end of the run.

A dynamotor is naturally less reliable than a wind driven generator when built within a practical weight limit. It is necessary to work the windings as hard as possible, and failure from overheating may result if the duty cycle for which the dynamotor is designed is exceeded. The high tension winding of a direct-current dynamotor requires very fine wire so that a mechanical failure of the winding may occur unless extreme care is taken in the winding of the armature.

The engine driven battery charging generator must be included in any consideration of reliability, although a failure of the charging generator will not prevent operation of the equipment until the battery is exhausted. An airplane engine does not have a flywheel and the

torque delivered is pulsating. To protect the generator and to prevent loosening of the armature laminations on the generator shaft, it is necessary to provide a shock absorbing coupling between the engine and the generator. Practically all of the couplings in use are subject to failure, since they use springs or rubber as the shock absorbing medium. A coupling failure, however, will not necessarily prevent the operation of the generator.

The voltage regulator is usually a source of considerable difficulty. Reports of regulator operation are extremely conflicting. It is said that one transport company has had so much difficulty with regulators that it has instructed its pilots to disconnect them altogether and to control the voltage with a field rheostat which has to be reset after each change in engine speed. On the other hand some users of voltage regulators state that absolutely no trouble is experienced with them.

The amount of energy that can be interrupted by a set of vibrating contacts without burning is extremely small even with the best contact materials obtainable. There is also a limit to the amount of current which can be carried with the contacts closed. Consequently, the difficulties in applying a voltage regulator increase rapidly with the size of the generator. On the whole it is probably correct to assume that the vibrating regulator is not very reliable.

The dynamotor system requires considerably more maintenance than the wind driven generator. Both the dynamotor and the charging generator require the usual maintenance for rotating machinery and in addition the dyanamotor starting relay, the vibrating regulator, and the flexible coupling will require attention.

The equivalent weight of the dynamotor depends upon the losses in the engine driven generator, the battery, and the dynamotor. The efficiency of the engine driven generator will be about 60 per cent. Only the losses in the battery resulting from the fact that the battery must supply current in generating high tension power can be included and a factor of 0.95 is arbitrarily assumed to take care of the battery losses. The direct-current dynamotor has an efficiency of about 60 per cent. For the over-all efficiency of an alternating-current dynamotor and rectifier the value of 50 per cent will be assumed.

The power required from the engine will be:

$$\text{d.c.} — \frac{300}{0.6} + \frac{400}{0.6 \times 0.95 \times 0.6} = 1670 \text{ watts.}$$

$$\text{a.c.} — \frac{300}{0.6} + \frac{400}{0.6 \times 0.95 \times 0.5} = 1904 \text{ watts.}$$

The corresponding equivalent weight will be 44 pounds for the direct-

current dynamotor and 50.1 pounds for the alternating-current dynamotor.

The total effective weight will be:

	Direct Current	1000-Cycle Alternating Current
Dynamotor	26.5 lb.	28 lb.*
65 amp-hr. battery	70	70
Cables	10*	10*
Starting relay	2	2
50-ampere generator and control box	47	47
Rectifier unit		10
Total actual weight	155.5	167
Equivalent weight	44	50
Effective weight	199.5	217

* Estimated values.

The advantages of the dynamotor system are:

1. A limited amount of emergency operation is provided.
2. The electrical performance is fairly good.

The disadvantages are:

1. The equipment is extremely heavy.
2. Considerable space is required.
3. Considerable maintenance is required.
4. A failure of the battery charging generator may put the main engine out of commission.

The Double Voltage Main Engine Driven Generator

The next system to be considered is the double voltage main engine driven generator with a vibrating voltage regulator. It is the most direct method of obtaining power from the main engine and should be the most efficient method. Because of the varying speed of the generator this system cannot be used for alternating current and this is one of its serious disadvantages.

The generator itself is of conventional design. Both four-pole and two-pole generators are used, the former having a very slight advantage in weight and the latter having a very considerable advantage in reliability. The size of the generator is limited by the space available on the engine and also by the fact that it must be mounted on the standard Army-Navy mounting. The largest generators now in use have a height of 12 in. and a maximum diameter of 6 in. The generator must operate at a fairly low speed, usually about 2200 r.p.m. and is

consequently heavy for its output as compared with the wind driven generator. Engine driven generators may be ventilated by means of a suction tube extending into the slip stream or they may depend merely on the natural circulation of air around the main engine for ventilation.

A double voltage generator is much larger than a battery charging generator and consequently it is difficult to provide a suitable voltage regulator and shock absorbing coupling. At present the vibrating type of regulator is used exclusively, although some experimental work has been done with other types of regulators.

The performance of the double voltage engine driven generator depends largely upon the voltage regulator. Under the best of conditions there is considerable interference from the regulator. For a long time it was believed that it would be impossible to use a voltage regulated generator for telephone communication, although this has now been accomplished. There are, however, very few double voltage engine driven generators in use and practically none of these are used with telephone transmitters.

The voltage regulation on the battery charging winding is fixed by the regulator and is practically perfect when the regulator is operating correctly. The high tension voltage regulation is usually worse than that of a wind driven generator, but considerably better than that of a dynamotor.

No emergency communication is available with an engine driven generator, although in the case of multimotored airplanes it may be possible to shift the generator to an engine which has not failed or been damaged in landing. It is also possible to provide a generator on more than one engine at considerable increase in weight. Emergency communication has also been provided by carrying a thirty or forty pound auxiliary gasoline engine to which the generator can be coupled when necessary.

The equipment is probably less reliable than either the direct-current wind driven generator or the direct-current dynamotor, and is certainly less reliable than any form of alternating-current system. In addition to the possibility of failure of the generator there is also the possibility of failure of the regulator.

In addition to the usual generator maintenance a great deal of attention is required by the regulator.

The efficiency of an engine driven generator is fairly low, because of the low operating speed and the poor space factor in the high tension winding. The efficiency will be about 55 per cent and the power required from the engine will be $700/0.55 = 1270$ watts. The equivalent

weight is 1270/38 = 33.5 pounds. The weight will be based upon the use of a two-pole generator, because of the superior reliability of that type. The effective weight is as follows:

	Direct Current
700-watt generator	50 lb.
Control box	3
Cables	6*
38 amp-hr. battery	36
Total actual weight	95
Equivalent weight	33.5
Total effective weight	128.5

* Estimated value.

The advantages of the engine driven generator are:

1. The effective weight is low since only one conversion of power is required.
2. No cargo space is required by the generator.

The disadvantages are:

1. The mounting space is too restricted for the best design.
2. The operating speed is too low for securing a minimum generator weight.
3. The voltage regulator causes considerable electrical disturbance.
4. The reliability is inferior to that of other types of equipment.
5. No emergency communication can be provided.
6. Considerable maintenance is required.
7. An alternating-current generator cannot be used, because of the variable speed.
8. A failure of the generator may put the main engine out of commission.

Auxiliary Engine Generator Set

An auxiliary engine coupled to a generator so as to make the power equipment entirely independent of the main engine is in many ways an ideal power system. The advantages of this system become greater as the rating of the power equipment is increased. The generating equipment on the Dornier Do-X flying boat is driven by a 12-horsepower auxiliary engine. Emergency communication is possible at all times if fuel is available and the same engine that drives the generating equipment is used for pumping out the hull.

This type of power equipment has not yet been used in this country for heavier-than-air ships, because it is felt to constitute a fire hazard on present types of airplanes and also because very few airplanes have

the necessary space for its installation. If the use of Diesel engines becomes general, it is likely that the small amount of gasoline required for an engine generator set will not cause any appreciable fire hazard.

The performance of an auxiliary engine generator set is very good. A four-cycle engine is used so that the speed of the engine can be governed closely. Either a direct-current or an alternating-current generator can be used and no voltage regulator is required. The set can be operated at a speed as high as 4000 r.p.m. so that a lightweight generator can be used.

The reliability of this system depends upon that of the engine. No experimental data are available for such a lightweight, high speed engine operating under the conditions of airplane service. Such ground tests as are available indicate that the engine can be made to be extremely reliable.

The maintenance which would be required would be changing the engine oil every ten hours, overhauling the engine every 200 hours and the usual attention required by the generator.

The engine will consume about one and one-half pounds of gasoline per hour for an electrical output of 700 watts. For a ten-hour flight, therefore, the average weight of fuel carried will be seven and one-half pounds, i.e., fifteen pounds at the start of the flight and nothing at the end of the flight.

The total weight of the equipment will be:

	Direct Current	800-Cycle Alternating Current
Engine generator	100 lb.	90 lb.
Average fuel	7.5	7.5
Cables, etc.	15*	5*
38 amp-hr. battery	36	36
Rectifier		10
Actual weight	160.5	150.5
Equivalent weight	0	0
Effective weight	160.5	150.5

* Estimated values.

The advantages of the engine generator set are:

1. The set has a full-time emergency rating.
2. Either direct or alternating current can be used.
3. No voltage regulator is required.
4. Good voltage regulation is secured.
5. Good reliability should be secured.

6. The equipment is entirely independent of the main engine so that failure of the generating equipment cannot put the main engine out of commission.
7. The engine may be used for mechanical power such as for operating a bilge pump on a seaplane.

The disadvantages are:

1. A fire hazard exists unless the set is carefully installed.
2. An engine generator cannot be installed in the majority of present airplanes.
3. The engine loses power at extreme altitudes.

The Combination Wind Driven Generator and Dynamotor

From time to time efforts have been made to secure emergency operation from a wind driven generator by operating it as a dynamotor from the storage battery. The ordinary wind driven generator will give only from 50 to 60 per cent of its normal high tension voltage when operated as a dynamotor from a battery which it is capable of charging. The reason for this is that the low tension IR drop increases the voltage ratio of the two windings when the machine is operated as a generator and decreases the voltage ratio when the machine is operated as a dynamotor.

The combination wind driven generator and dynamotor was developed to give full power for emergency operation. The same high tension voltage is generated when the machine is operated as a generator with a low tension voltage of 14.6 volts as is generated when the machine is operated as a dynamotor with an input voltage of 11 volts. Two low tension commutators and windings are necessary to accomplish this. A constant speed propeller is now available with an overrunning device so that it is not necessary to drive or remove the propeller when the machine is operated as a dynamotor.

During normal operation the voltage regulation will be slightly poorer than that of a conventional wind driven generator, but otherwise the electrical performance will be very good.

The reliability will be similar to that of a wind driven generator. The efficiency during normal operation will be less than that of the conventional wind driven generator and will probably be about 50 per cent for either direct current or for alternating current.

The equivalent weight will be

$$\frac{700}{0.5 \times 0.75 \times 0.7} \times \frac{1}{38} = 70.3 \text{ pounds}.$$

The effective weight will be:

	Direct Current	800-Cycle Alternating Current
Generator dynamotor	36 lb.*	36 lb.*
65 amp-hr. battery	70	70
Propeller	6.25	6.25
Cables	15*	15*
Relays and switch	6*	6*
Rectifier unit		10
Total actual weight	133.25	143.25
Equivalent weight	70.3	70.3
Effective weight	203.55	213.55

* Estimated values.

Most of the above figures have not yet been finally determined, but it is not likely that these weights will be changed materially. It will be seen that the effective weight is less than that obtained for the conventional dynamotor system, because of the elimination of the engine driven battery charging generator.

The advantages of this system are:

1. Emergency communication is provided.
2. No voltage regulator or engine driven generator is required.
3. The voltage regulation is fairly good.
4. Either direct or alternating current can be used.
5. The machine is ventilated in normal service.
6. No cargo space is required.
7. Very little maintenance is required.
8. The reliability is good.
9. The machine can be used on any airplane.
10. The power equipment is independent of the main engine and a failure of the power equipment cannot put the main engine out of commission.

The disadvantages are:

1. The weight is fairly high.
2. The wiring is complicated.

The Constant Speed Main Engine Driven Alternator

A constant speed alternator driven directly by the main engine has been recently developed, although it is not yet commercially available. This machine makes it possible for the first time to combine the use of alternating current for high reliability with the use of main engine drive for economy and simplicity.

The experimental models which are now undergoing flying tests were not designed for battery charging, although direct current is provided for excitation so that it will be easy to incorporate the battery charging feature. A centrifugally controlled friction drive operates the generator at practically constant speed over the entire range of engine speeds from slightly below cruising speed to the maximum speed obtained in a power drive. Excellent frequency regulation and voltage regulation are obtained.

No emergency operation is possible, although an auxiliary engine can be carried if emergency operation is necessary. The generator can be used on any motor of a multimotored airplane by bringing cables to each motor. The use of separate generators on two of the main engines would be possible at an increase in weight of about 25 per cent.

The machine should be extremely reliable as all parts are very rugged. Very few parts are required and none of them is likely to fail. No flexible coupling is necessary, since the friction drive absorbs the shocks from the engine.

Very little maintenance is required. Life tests have indicated that the life of the friction elements in the drive mechanism will be at least 500 hours. This is longer than an airplane engine is usually operated without being overhauled.

The over-all efficiency varies with the speed of the engine. At cruising speed the efficiency is about 70 per cent for the generator and drive and about 80 per cent for the rectifier, so that the equivalent weight is

$$\frac{700}{0.7 \times 0.8} \times \frac{1}{38} = \frac{1250}{38} = 33 \text{ pounds}.$$

The actual weight of the experimental 600-watt machine is 28 pounds. To determine the effective weight it will be necessary to estimate the weights from that of the experimental machine.

	450-Cycle Alternating Current
Generator	35 lb.*
Rectifier unit	15*
Battery relay	2
38 amp-hr. battery	36
Cables	4
Total actual weight	92
Equivalent weight	33
Effective weight	125

* Estimated values.

The advantages of this generator are:

1. Very low effective weight is obtained.
2. The drive from the main engine is simple and direct.
3. The constant speed mechanism is built into the generator.
4. No voltage regulator is required.
5. The use of alternating current insures high reliability.
6. No cargo space is required.
7. Very little maintenance is required.
8. The generator can be operated on practically any type of small engine for emergency operation.

The disadvantages are:

1. No emergency communication is possible.
2. A failure of the generator might put the main engine out of commission.

Conclusion

It has been evident from this discussion that no available type of power equipment can be regarded as entirely satisfactory. No one type of power equipment is sufficiently superior to other available types so that its use can be expected to become universal.

A pronounced tendency towards the use of main engine driven generators is very evident. The chief obstacle to the use of this type of generator is that emergency communication cannot be provided. It is possible that some type of combination engine driven generator and dynamotor will be developed to give emergency operation and it is also possible that airplanes will be perfected to such an extent that emergency communication will not be regarded as essential.

The auxiliary engine generator set has the greatest theoretical possibilities of any of the types of power equipment considered. By combining the engine and generator into a single unit it would appear that an output of 700 watts could be secured with a set weighing about fifty pounds. It is likely that the power required by the larger airplanes will increase a great deal in the future and in this case the engine generator set becomes the only practical source of power.

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POLYPHASE RECTIFICATION SPECIAL CONNECTIONS*

By

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Summary—*Characteristics of various rectifier circuits and factors governing their selection are given. It is pointed out that in general, the double 3-phase circuit is most desirable from the standpoint of transformer and tube capacity requirements for mercury pool type tubes, and the 6-phase single Y for hot cathode mercury vapor tubes or high vacuum tubes, but that other factors may make other circuits more desirable for particular cases. Data are given for 3-, 4-, 6-, and 12-phase rectifiers using T-connected transformers, so that fewer transformers are required. Since it is cheaper to build two large transformers than three smaller ones of approximately the same total capacity, the T-connection may permit a saving in transformer cost. The voltage doubling circuit is discussed, its relation to other single phase circuits shown, and its characteristics given as a function of the product, CR, of condenser capacity and load resistance.*

Introduction

A NUMBER of factors are involved in the determination of the best rectifier circuit for a radio application, so that no one circuit can be considered best for all applications, and a knowledge of the characteristics of possible circuits is necessary for the selection of the proper circuit for a particular case. The d-c output voltage and current requirements may determine the type of rectifier tube, whether high vacuum tube, hot cathode mercury vapor, or pool-type mercury vapor; and both the d-c rating and the type of tube, as well as the permissible ripple in the output, affect the choice of circuit. The high vacuum tube is best adapted to quite high voltage and low current, and the mercury vapor types up to moderately high voltages and to larger currents. Both mercury vapor types have their peculiar starting characteristics and require special starting arrangements. The pool type is the better for applications where short circuits or overloads are likely to occur, due to the fact that excessive instantaneous currents are apt to damage the filament of the hot cathode type. In general the limit for high vacuum tubes or hot cathode tubes is the peak current, whereas for the mercury pool type it is more nearly the r.m.s. current, that is, that determining the heating.

Radio applications are usually for a definite d-c load with no need to provide for gradual future expansion, and since with glass bulb

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rectifiers it is necessary to use standard sizes, it is desirable to choose a combination of circuit and tubes which will make the tubes operate at about their full load rating. This is important in applications requiring economy of weight and space. Other considerations in the choice of circuit are whether the transformers are to be special or standard or whether those on hand must be used; the relative advantage of investing in few tubes and a large transformer or more tubes and a smaller transformer; and in one case (the 6-phase star with star primary) whether both supply system and rectifier transformer primary have grounded neutral. The factors will be more evident in the discussion of particular circuits.

I. Characteristics of Typical Circuits

Table I gives characteristics of typical rectifier circuits. In the calculation of these values, the usual assumptions, [(1), (2), (3), †] have been made; that is, transformer exciting current and impedance, and rectifier tube drop are neglected; and it is assumed that the supply voltage is sine wave, and the choke coil in the d-c line is large enough to maintain the d-c current constant. The values obtained in this way, while not taking care of voltage drop in the system, are very useful in the comparison of different types of circuits.

Considering the circuits of Table I, the single phase full wave circuit is the most commonly used for single phase supply. (The half wave circuit, not shown in Table I, is seldom used, except with a condenser, for small currents, because the secondary current flows through the transformer always in the same direction, which has a bad effect on the iron, and because without the use of a condenser, it is impossible for a choke coil to maintain the d-c current over a complete cycle). A comparison of the data for the full wave circuit with that for the single phase bridge circuit shows that the full wave circuit requires more average transformer kva, and half as many tubes, worked at twice the voltage. The fact that thermionic tubes are most efficient at high voltage, due to their constant internal drop, usually decides in favor of the full wave type. With the full wave type there is the drop of only one tube in series with the load whereas with the bridge circuit there is the drop of two. Also the bridge circuit requires a more complicated filament supply, since two of the filaments must be insulated. However, for rectifiers such as the copper oxide disk, where the drop is approximately a percentage drop, the bridge circuit requires no more volt ampere capacity of rectifier units, and gives a saving in transformer size.

† See bibliography.

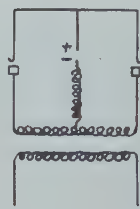
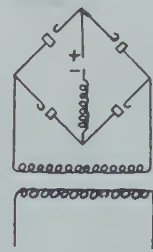
TYPE	SINGLE PHASE FULL WAVE	SINGLE PHASE BRIDGE CIRCUIT	4 PHASE STAR 2 PHASE SUPPLY
CIRCUITS: SECONDARIES / PRIMARIES			
RECTIFIER PHASE AND NUMBER OF TUBES	2	2-4	4
NUMBER OF PHASES OF SUPPLY	1	1	2
TRANSFORMER SECONDARY VOLTAGE PER LEG	1.11 (HALF SECTION)	1.11 (WHOLE)	0.785
TRANSFORMER PRIMARY VOLTAGE	1.11	1.11	0.785
TRANSFORMER SECONDARY CURRENT PER LEG	0.707	1	0.500
TRANSFORMER PRIMARY CURRENT PER LEG	1	1	0.707
TRANSFORMER SECONDARY K.V.A	1.57	1.11	1.57
TRANSFORMER PRIMARY K.V.A.	1.11	1.11	1.11
AVERAGE OF PRIMARY AND SECONDARY K.V.A.	1.34	1.11	1.34
PEAK VOLTAGE ACROSS TUBE (INVERSE)	3.14	1.57	2.22
CURRENT PER TUBE	0.707	0.707	0.50
PEAK CURRENT PER TUBE	1.00	1.00	1.00
VOLTAGE RIPPLE FREQUENCY	2f	2f	4f
RIPPLE VOLTAGE	0.483	0.483	0.098
RIPPLE PEAKS WITH REFERENCE TO AVERAGE D.C. AS AXIS. +	0.363	0.363	0.111
RIPPLE PEAKS WITH REFERENCE TO AVERAGE D.C. AS AXIS. −	0.637	0.637	0.215
LINE VOLTAGE	1.11	1.11	0.785
LINE CURRENT	1.00	1.00	0.707
LINE POWER FACTOR	0.90	0.90	0.90
FREQUENCY OF BALANCE COIL VOLTAGE	—	—	—
BALANCE COIL VOLTAGE	—	—	—
PEAK BALANCE COIL VOLTAGE	—	—	—
BALANCE COIL K.V.A.	—	—	—

TABLE IA.

Circuit Data for Typical Rectifiers

The values of voltage and current are effective or r.m.s., unless otherwise stated; they are given in terms of the average d-c values, and the kilovolt-amperes in terms of d-c kilowatt output. Perfect transformers, rectifiers, and d-c choke are assumed.

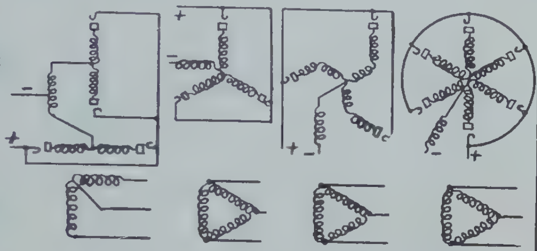
TYPE	DOUBLE 2 PHASE WITH BALANCE COIL. 2 PHASE SUPPLY	3 PHASE STAR	3 PHASE BROKEN STAR	6 PHASE STAR 3 PHASE SUPPLY
CIRCUITS: SECONDARIES, PRIMARIES				
RECTIFIER PHASE AND NUMBER OF TUBES	4	3	3	6
NUMBER OF PHASES OF SUPPLY	2	3	3	3
TRANSFORMER SECONDARY VOLTAGE PER LEG	1.11	0.855	0.985 (HALF LEG 4.93)	0.740
TRANSFORMER PRIMARY VOLTAGE	1.11	0.855	0.855	0.740
TRANSFORMER SECONDARY CURRENT PER LEG	0.354	0.577	0.577	0.408
TRANSFORMER PRIMARY CURRENT PER LEG	0.500	0.471	0.408	0.577
TRANSFORMER SECONDARY KVA	1.57	1.48	1.71	1.81
TRANSFORMER PRIMARY KVA.	1.11	1.21	1.21	1.28
AVERAGE OF PRIMARY AND SECONDARY KVA	1.34	1.35	1.46	1.55
PEAK VOLTAGE ACROSS TUBE (INVERSE)	3.14	2.09	2.09	2.09
CURRENT PER TUBE	0.354	0.577	0.577	0.408
PEAK CURRENT PER TUBE	0.50	1.00	1.00	1.00
VOLTAGE RIPPLE FREQUENCY	4f	3f	3f	6f
RIPPLE VOLTAGE	0.098	0.183	0.183	0.042
RIPPLE PEAKS WITH REFERENCE TO AVERAGE D.C AS AXIS. +	+ 0.111	0.209	0.209	0.0472
RIPPLE PEAKS WITH REFERENCE TO AVERAGE D.C AS AXIS. −	− 0.215	0.395	0.395	0.930
LINE VOLTAGE	1.11	0.855	0.855	0.740
LINE CURRENT	0.50	0.817	0.707	0.817
LINE POWER FACTOR	0.90	0.826	0.955	0.955
FREQUENCY OF BALANCE COIL VOLTAGE	—	—	—	—
BALANCE COIL VOLTAGE	—	—	—	—
PEAK BALANCE COIL VOLTAGE	—	—	—	—
BALANCE COIL K.V.A.	—	—	—	—

TABLE IB.

Circuit Data for Typical Rectifiers

The values of voltage and current are effective on r.m.s., unless otherwise stated; they are given in terms of the average d-c values, and the kilovolt-amperes in terms of d-c kilowatt output. Perfect transformers, rectifiers and d-c choke are assumed.

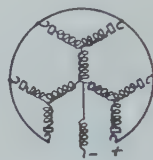
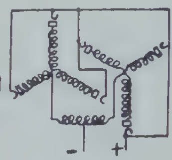
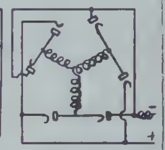
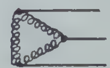
TYPE	6 PHASE BROKEN STAR 3 PHASE SUPPLY	DOUBLE 3 PHASE WITH BALANCE COIL	6 PHASE SINGLE Y
CIRCUITS — SECONDARIES			
PRIMARIES			
RECTIFIER PHASE AND NUMBER OF TUBES	6	6	6
NUMBER OF PHASES OF SUPPLY	3	3	3
TRANSFORMER SECONDARY VOLTAGE PER LEG	0.428 (PER SECTION OF LEG)	0.855	0.428
TRANSFORMER PRIMARY VOLTAGE	0.428	0.855	0.428
TRANSFORMER SECONDARY CURRENT PER LEG	INNER SECT. 0.577 OUTER SECT. 0.408	0.289	0.816
TRANSFORMER PRIMARY CURRENT PER LEG	0.816	0.408	0.816
TRANSFORMER SECONDARY K.V.A.	1.79	1.48	1.05
TRANSFORMER PRIMARY K.V.A.	1.05	1.05	1.05
AVERAGE OF PRIMARY AND SECONDARY K.V.A.	1.42	1.26	1.05
PEAK VOLTAGE ACROSS TUBE (INVERSE).	2.09	2.42	1.05
CURRENT PER TUBE	0.408	0.289	0.577
PEAK CURRENT PER TUBE	1.00	0.500	1.00
VOLTAGE RIPPLE FREQUENCY	6f	6f	6f
RIPPLE VOLTAGE	0.042	0.042	0.042
RIPPLE PEAKS WITH REFERENCE TO AVERAGE D.C. AS AXIS +	0.0472	0.0472	0.0472
RIPPLE PEAKS WITH REFERENCE TO AVERAGE D.C. AS AXIS −	0.0930	0.0930	0.0930
LINE VOLTAGE	0.428	0.855	0.428
LINE CURRENT	1.41	0.707	1.41
LINE POWER FACTOR	0.955	0.955	0.955
FREQUENCY OF BALANCE COIL VOLTAGE	—	3f	—
BALANCE COIL VOLTAGE	—	0.356	—
PEAK BALANCE COIL VOLTAGE	—	0.605	—
BALANCE COIL K.V.A.	—	0.178	—

TABLE IC.

Circuit Data for Typical Rectifiers

The values of voltage and current are effective on r.m.s., unless otherwise stated; they are given in terms of the average d-c values, and the kilovolt-amperes in terms of d-c kilowatt output. Perfect transformers. rectifiers and d-c choke are assumed.

The data for the 4-phase star and the double 2-phase circuits with two phase supply, show that with these circuits the chief gain over the single phase full wave circuit is the decrease in the d-c ripple voltage and the increase in its frequency, there being no decrease in the transformer kva rating required. The 4-phase star, however, has a smaller maximum voltage across the tubes.

The 3-phase star circuit with single phase transformers has the same disadvantage that the half wave single phase rectifier has, in that current flows in the transformer secondary in one direction only, putting a d-c component of flux in the iron and causing high iron loss. The 3-phase broken star circuit overcomes the disadvantage of current flow in only one direction, by forming each secondary leg of half the transformer winding of two different phases. However, since the two voltages of the two parts of each secondary leg are not in phase, a higher secondary voltage rating is required, and the kva, as shown in the table, is greater.

The data for the 6-phase star connection with delta primary along with the data for the 4-phase and 3-phase connections illustrate the fact that the secondary current rating of the single star arranged so that current can flow in one phase only, goes up with increase of the number of phases, since each phase carries current a shorter period of time; and that the transformer secondary voltage approaches the value 0.707 d-c voltage, i.e., the d-c voltage approaches the a-c peak voltage. Marti[2] has shown also, that considering the secondary reactance, the reactance voltage drop goes up as the number of phases. The 6-phase broken star or triple Y is a scheme for keeping down the transformer kva. It effects a saving in the ratio of 1.42 to 1.55 as shown in the table, but requires more complicated transformer connections. If the 6-phase star secondary were used with a 3-phase star primary without neutral connection, instead of with a delta primary, the current could not flow from one phase only, but (except for the line current) the system would operate as, and have the characteristics of the double 3-phase system, the transformer reactance taking the place of the balance coil of the usual double 3-phase, as has been shown by E. Gerecke.[4] If the neutral of the primary became grounded, and the neutral of the supply system was grounded, the secondary would operate the same as with the delta primary except that the line current would be the same as the transformer current and hence have third harmonics. If with the primary neutral ungrounded, a tertiary winding were added to the transformers, the secondary current would be the same as with delta primary, but the primary current would have the same wave shape as the line current

for the double 3-phase with delta primary, and therefore put no third harmonics on the line, and have better voltage regulation characteristics.

The double 3-phase circuit is one of the best 6-phase arrangements[5] since it gives the advantage of 6 phase in regard to ripple, yet has a fairly low value of transformer kva. The balance coil acts to make each group of three phases carry half the current all the time so that each group operates as 3 phase and requires the same transformer secondary kva as 3 phase. The primary, however, now carries the same current for two-thirds of the time in both half cycles, and so has a smaller kva than for simple 3 phase. The instantaneous d-c voltage, being the average of the two overlapping 3-phase groups, has the same ripple frequency and the same per cent ripple as 6 phase. This paralleling of the two 3-phase groups could also be accomplished by using an individual choke in series with each 3-phase group, but the chokes would have to be very large to prevent saturation of the iron core. With the balance coil the d-c components of flux cancel due to the autotransformer action between the two halves; so that the balance coil can be much smaller than the equivalent pair of choke coils, and a small choke designed for twice the frequency of the two chokes can be used to take out the 6-phase ripple.

By putting the two 3-phase groups in series instead of parallel the same desirable characteristics are obtained without the use of a balance coil. However, the values of transformer voltage should be divided by two, the peak inverse voltage across tube changed to 1.05, and the values of transformer current and of peak current per tube in the table should be multiplied by two to fit the series arrangements. Parallel and series arrangements can be used for more than 6 phases, for instance 12 phase, and the various combinations of groups of 3 phase in series or in parallel with balance coil, allows a limited number of stock sizes of rectifier tubes to be adapted to a wide range of applications. These combinations are especially useful with mercury pool type rectifier tubes. When a series and parallel combination of 3-phase units is used it should be an arrangement of series groups paralleled with balance coils, rather than an arrangement of groups of single units paralleled and then the groups put in series, since the former arrangement requires fewer balance coils, and less voltage, of a higher frequency, across the coils, and hence less investment in balance coils.

Another 6-phase circuit which has very desirable characteristics is the 6-phase single Y. It has the advantage of 6 phase, and gives the lowest transformer kva of any of the circuits in Table I. Since the peak

tube current is twice and the transformer voltage half that for the double 3 phase with balance coil, this connection corresponds to two 3-phase groups in series rather than to the two in parallel. Two of the 6-phase single Y groups can be connected in parallel or in series for 12-phase operation. This circuit, where it fits the voltage requirements, is perhaps the best 6-phase circuit for high vacuum tubes or hot cathode mercury vapor tubes, but cannot be used with pool-type mercury vapor tubes because it requires a separate insulated cathode for each anode, and the pool-type tubes require at least two, and usually three anodes per cathode, so that at least one anode is drawing an arc from the cathode all the time, to prevent extinction of the arc. It could be used, of course, with mercury-type tubes built with a single power anode and a pair of auxilliary keep-alive anodes.

Little has been said in the discussion above about the relative amount of voltage regulation of the various circuits for the same per cent 60-cycle transformer reactance. In general, however, it can be said that the circuits having a low transformer kva rating in terms of the d-c kw output and a high line power factor will have a smaller per cent regulation than those with a high kva rating and lower line power factor. This is apparent from the fact that the increase of the transformer regulation, in rectifier service, over that in normal 60-cycle operation value is related to the harmonics in the transformer current, and that in most of the rectifier circuits the value of the transformer kva rating is an indication of the amount of harmonics present. Since in most rectifier circuits the variation of the kva to kw ratio from unity, is due to a variation of the current wave shape from the sine wave shape, and not due to a phase difference between current and voltage, the kva rating gives an indication of the amount of harmonics, though not of their frequency. This does not hold for arrangements such as the broken star connections, and the T-connections described in the following section, since in part of the transformer windings of these circuits the voltage and current are not exactly in phase.

II. Circuits with T-connected Transformers

In the selection of a circuit with a low kva rating, the object is mainly, of course, to keep down transformer cost. R. L. Davis[1] (under whose direction the rectifier calculations were largely done) showed the writer that it is possible to use only two transformers, T-connected in place of the usual three transformers on 3-phase supply,

[1] Manager, Radio Engineering Department, Westinghouse Electric and Manufacturing Company, Chicopee Falls, Massachusetts.

and that the total kva of the T-connection is only slightly higher than the usual 3-transformer arrangement. Since it is cheaper to build two large transformers than three smaller ones of about the same total capacity, the use of the T connection should give a saving in transformer cost. The T connection provides another method of avoiding a d-c component of flux in the iron for the 3-phase rectifier and compares favorably with the 3-phase broken star discussed in Section I.

With the T-connected transformers it is necessary that the different windings of each transformer be well interwoven to give minimum reactance and maximum autotransformer action between sections. This requirement will be evident in the following calculation of transformer rating.

In the calculation of the rating for the T connection, the same assumptions are made as for the connections of Table I, i.e., it is assumed that the supply voltage is sine wave and that the transformers are a 1:1 ratio, and the choke coil in the d-c line is large enough to maintain the d-c current constant; and transformer exciting current, resistance and reactance, and rectifier tube drop are neglected. The following symbols will be used:

G = average d-c voltage
J = d-c current
E = effective a-c voltage
I = effective a-c current
e = instantaneous voltage
i = instantaneous current
$\mathcal{E}$ = maximum value of sine wave voltage

Subscripts refer to the location in the circuit.

For the 3-phase rectifier, consider Fig. 1 where AD and ad are the secondary and primary respectively of the teaser transformer, and CB and cb are the secondary and primary of the main transformer. The secondary of the teaser transformer has a tap, N, at two-thirds the distance from A to D which forms the negative d-c lead and both primary and secondary of the main transformer have a mid-tap for connection to the teaser transformer. The three secondary phase voltages measured from the neutral point, N, are represented for the positive half cycles by e_A, e_B, and e_C. Each phase will carry the full d-c current, J, while its voltage is higher than either of the adjacent phases, and will carry zero current the remainder of the cycle. This gives the currents i_{NA}, i_{DB}, and i_{DC} as shown, and also $i_{ND} = i_{DC} + i_{DB}$. For primary current to flow without a high reactance drop it is necessary for each section of the secondaries to have minimum leakage reactance with respect to the whole of the corresponding primary, and for

the two halves of the main transformer primary to have minimum leakage with respect to each other, to give maximum autotransformer action, and so, allow current from the teaser primary to divide and flow each way through the halves of the main transformer primary winding. Under these conditions, when current J flows in section NA of the teaser secondary, the current in the teaser primary, since $NA = 2/3$

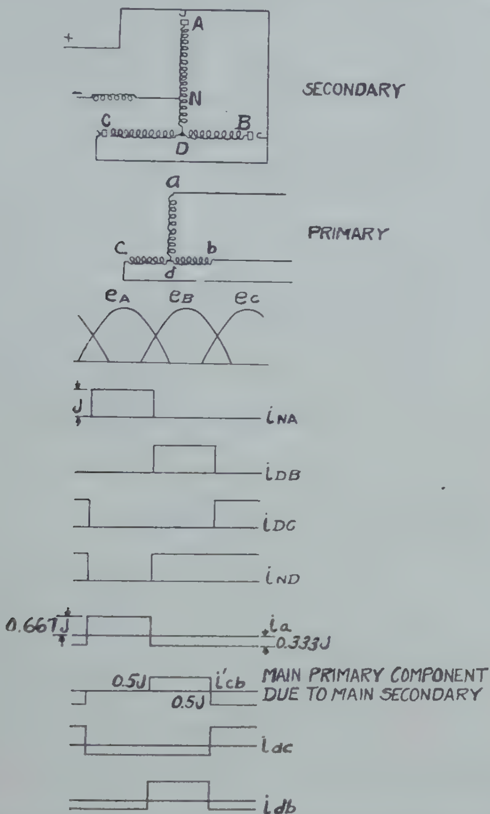


Fig. 1—Circuit diagram and voltage and current wave forms for 3-phase rectifier with T-connected transformers.

the number of turns of the whole primary, $= 0.667J$. Likewise, when current J flows in ND the primary current will be $0.333J$, in the opposite direction to that due to the current in NA, giving the total teaser primary current i_a as shown.[2] The main transformer primary has two components of currents, one due to the current in the main transformer secondary, and the other, the teaser primary current

[2] The fact that the primary currents actually flow in the opposite sense to the flow of the secondary currents has been neglected in this discussion.

which divides at d and flows, half through one-half the main primary, and the other half through the other half of the main primary. The currents i_{cd} and i_{db} obtained by adding and subtracting, respectively, i_a from the component due to the main transformer secondary are shown in Fig. 1.

The voltage and current wave shapes being determined, the r.m.s. or effective values are obtained as follows:

$$I_{NA} = \sqrt{J^2 \times 1/3} = J/\sqrt{3} = 0.577J = I_{DB} = I_{DC}$$
$$I_{ND} = \sqrt{J^2 \times 2/3} = \sqrt{0.667}J = 0.816J.$$

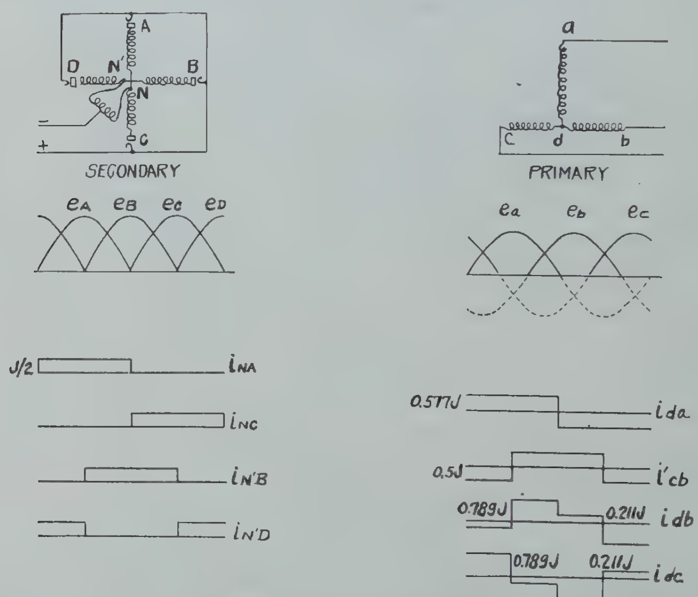


Fig. 2—Circuit diagram and voltage and current waves for 4-phase T-connected rectifier. i'_{cb} = main transformer primary current component due to main transformer secondary current.

As for the ordinary 3-phase circuit of Table I, the average d-c voltage, G, is equal to the average of one phase over the period during which it carries current or $G = (1/2\pi/3)\int_{\pi/6}^{5\pi/6}\mathcal{E}$ sin $\theta d\theta = (3\mathcal{E}/\pi)\int_{\pi/6}^{\pi/2}$ sin $\theta d\theta = (3\mathcal{E}/\pi)$ $(-\cos\ \theta)_{\pi/6}^{\pi/2} = (3\mathcal{E}/\pi)$ $(0+0.866) = 0.827\mathcal{E}$. Now the effective a-c phase voltage, E, $= 0.707\mathcal{E}$. Therefore, $E = G \times 0.707\mathcal{E}/0.827\mathcal{E} = 0.855G$.

$$E_{AN} = E = 0.855G$$

$$E_{ND} = 1/2E_{AN} = 0.428G$$

$$E_{CD} = E_{DB} = E_{AN} \cos 30 \text{ deg.} = 0.855G \times 0.866 = 0.741G.$$

Multiplying the current and voltage for each section and adding gives $0.842GJ$ for the teaser transformer secondary kva and $0.855GJ$ for the main transformer secondary kva and 1.70 for the total secondary kva.

$$\text{For the primary, } I_a = I_b = I_c = \sqrt{1/3 \times (0.667J)^2 + 2/3(0.333J)^2} = 0.471J.$$

$E_{ad} = 1.5E_{AN} = 1.28G$ $E_{cb} = 2 \times 0.866 \times E_{AN} = 1.48G$ and the primary kva $= 0.471J$ $(1.28 + 1.48)G = 1.30GJ$. The average of primary and secondary kva equals $1.50GJ$, which is only very slightly larger than the value 1.46 for the 3-phase broken star 3-transformer circuit. Complete data is given in Table II.

Fig. 2 shows the voltage and current waves for a 4-phase rectifier with T-connected transformers for 3-phase supply. In this case the teaser transformer does not have a 1:1 ratio but has a ratio of 0.866:1. This makes the teaser primary current, $i_a = 1/0.866 I_A$.
Determining the r.m.s. values as above:

$$I_A = I_B = I_C = I_D = \sqrt{1/2 \times (J/2)^2} = J/2\sqrt{2} = 0.354J$$

$$I_a = \sqrt{(0.577J)^2} = 0.577J$$

$$I_{cd} = I_{db} = \sqrt{1/2 \times (0.789J)^2 + 1/2 \times (0.211J)^2} = 0.577J$$

$$G = (1/\pi) \int_0^\pi \mathcal{E} \sin \theta d\theta = 0.637\mathcal{E} \qquad E = 0.707\mathcal{E}$$

$$E = G \times 0.707/0.637 = 1.11G$$

$$E_A = E_B = E_C = E_D = E = 1.11G$$

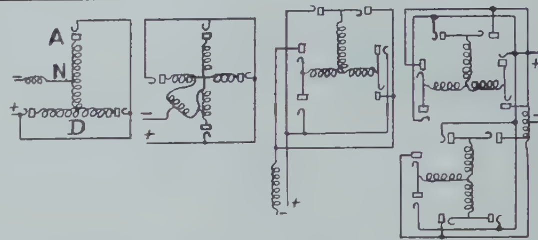
$$E_{ad} = 0.866 \times 1.11G = 0.961G \qquad E_{cb} = 1.11G.$$

Secondary kva $= 1.11 \times 0.354 \times 4GJ = 1.57GJ$.
Primary kva $= 0.577(0.9615 + 1.11)GJ = 1.20GJ$.
The average of primary and secondary kva is $1.38GJ$ compared to 1.34 given in Table I for 4-phase from 2-phase supply. The T-connection forms a convenient method of getting 4-phase from a 3-phase supply and would have an application where 3 tubes of standard size will quite give the required current output, but 4 tubes will.

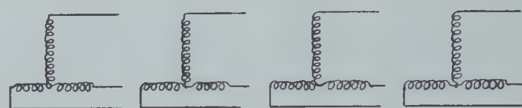
The 6-phase single T corresponding to the 6-phase single Y is another possible circuit using but two transformers. Its circuit and wave forms are shown in Fig. 3, the primary voltage and current waves being the same as the secondary. For this circuit

SECONDARIES

CIRCUITS
3PHASE SUPPLY



PRIMARIES



RECTIFIER PHASE AND NUMBER OF TUBES	3	4	6	12
TRANSFORMER SECONDARY VOLTAGE — TEASER	1.28 TAP AT 0.428		0.641	0.641
TRANSFORMER SECONDARY VOLTAGE — MAIN (WHOLE)	1.48 TAP AT 0.740	1.11	0.740 TAP AT 0.37	0.740 TAP AT 0.37
TRANSFORMER PRIMARY VOLTAGE — TEASER	1.28	0.962	0.641	0.641
TRANSFORMER PRIMARY VOLTAGE — MAIN	1.48 TAP AT 0.740	1.11	0.740 TAP AT 0.37	0.740 TAP AT 0.37
TRANSFORMER SECONDARY CURRENT — TEASER AN	0.577		0.816	0.408
TRANSFORMER SECONDARY CURRENT — TEASER ND	0.816	0.354	0.816	0.408
TRANSFORMER SECONDARY CURRENT — MAIN	0.577		0.816	0.408
TRANSFORMER PRIMARY CURRENT	0.472	0.578	0.816	0.788
TRANSFORMER SECONDARY K.V.A.	1.70	1.57	1.13	1.13
TRANSFORMER PRIMARY K.V.A.	1.30	1.20 1.28†	1.13	1.09 1.17†
AVERAGE OF PRIMARY AND SECONDARY K.V.A.	1.50	1.38 1.43†	1.13	1.11 1.15†
PEAK VOLTAGE ACROSS TUBE	2.09	3.14	1.05	1.05
PEAK CURRENT PER TUBE	1.00	0.50	1.00	0.50
FREQUENCY OF BALANCE COIL VOLTAGE	—	2f	—	6f
BALANCE COIL VOLTAGE	—	0.948	—	0.057
PEAK BALANCE COIL VOLTAGE	—	1.57	—	0.140
BALANCE COIL K.V.A.	—	0.474	—	0.029
VOLTAGE RIPPLE FREQUENCY	3f	4f	6f	12f
RIPPLE PEAK WITH REFERENCE TO AVERAGE D.C. AS AXIS +	0.209	0.111	0.0472	0.012
RIPPLE PEAK WITH REFERENCE TO AVERAGE D.C. AS AXIS −	0.395	0.215	0.0930	0.023
RIPPLE VOLTAGE	0.183	0.098	0.042	0.010

TABLE II.

CIRCUIT DATA FOR RECTIFIERS WITH T-CONNECTED TRANSFORMERS

Values of voltage and current are r.m.s. except where otherwise stated; voltage, current, and kva are given in terms of d-c output voltage, current, and kw respectively The same assumptions hold as for Table I plus values to make transformers interchangeable.

$$G = (1/\pi/6) \int_{\pi/6}^{\pi/3} \mathcal{E}[\sin\theta - \sin(\theta - 2\pi/3)]d\theta$$

$$= (6\mathcal{E}/\pi) \int_{\pi/6}^{\pi/3} [\sin\theta + \sin(\theta + \pi/3)]\,d\theta$$

$$= (6\mathcal{E}/\pi)[-\cos\theta - \cos(\theta + \pi/3)]_{\pi/6}^{\pi/3}$$

$$= (6\mathcal{E}/\pi)(0.5 + 0.866 + 0.5) = 1.65\mathcal{E}$$

$$E = 0.707\mathcal{E} = 0.707G/1.655 = 0.428G$$

$$E_{AD} = 1.5E = 0.641G \quad E_{CD} = E_{DB} = E \cos 30 \text{ deg.}$$

$$= 0.866 \times 0.428G = 0.370G$$

$$I_{AD} = I_{CB} = \sqrt{J^2 \times 2/3} = 0.816J.$$

Main transformer secondary kva $= 0.816J \times 2 \times 0.370G = 0.604GJ$. Teaser transformer secondary kva $= 0.816J \times 0.641G = 0.523GJ$. Total

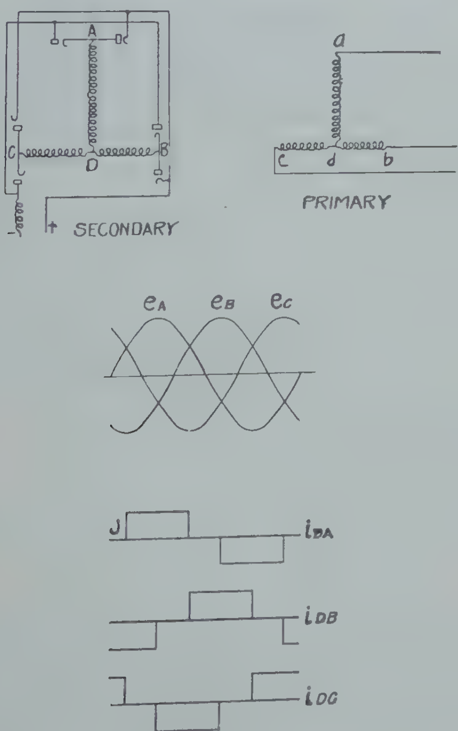


Fig. 3—Circuit diagram, and voltage and current waves for 6-phase T-connected rectifier.

secondary kva $=1.13GJ=$ total primary kva and the average is 1.13 compared to 1.05 for the conventional 6-phase single Y. The double 3-phase circuit is also possible with two T-connected transformers. It has the same secondary kva as the 3-phase circuit above, 1.70 GJ; and the same primary kva as the 6-phase single T, 1.13, giving an average kva of $1.41GJ$.

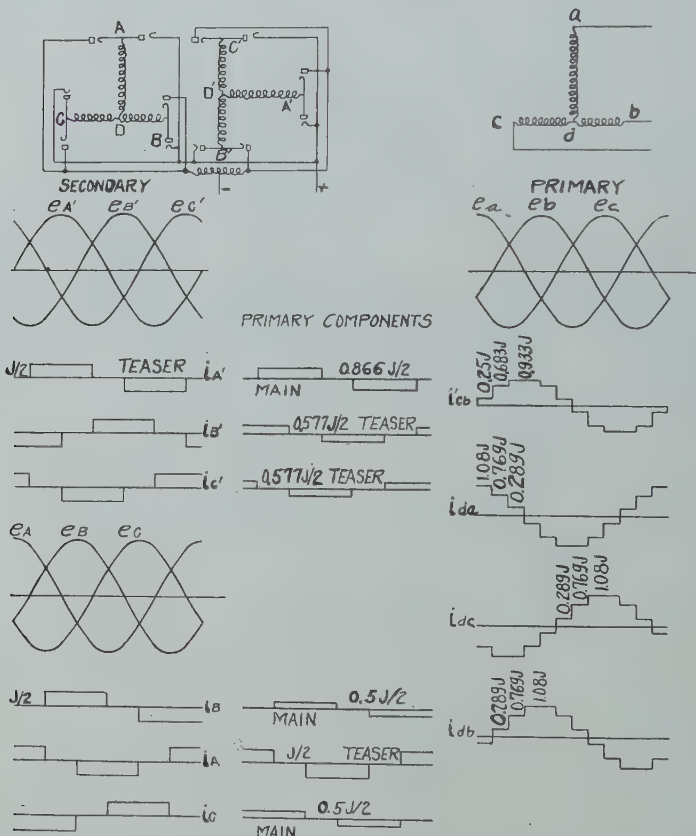


Fig. 4—Circuit diagram and voltage and current waves for 12-phase double-T rectifier. i'_{cb} = main transformer primary current component due to main transformer secondary current.

By using two secondary T's displaced in phase by 90 deg., twelve phases can be obtained in the form of a double 6-phase single T arrangement, as shown in Fig. 4. In the left-hand column of Fig. 4 are shown the secondary voltages and currents, and in the middle column, the primary current components due to the corresponding secondary currents. In the right-hand column are shown the primary voltages; the main transformer primary current component, i'_{cb},

which is the resultant of the main transformer current components of the middle column; the resultant teaser transformer primary current, i_{da}; and the currents $i_{dc}=-i'_{cb}-i_{da/2}$ and $i_{db}=i'_{cb}-i_{da/2}$.

Calculating the r.m.s. values of current, the secondary current, $I_{DA}=\sqrt{(J/2)^2\times 2/3}=0.408J=I_{DB}$, etc. and the primary current $I_{da}=\sqrt{1/3\times(1.08J)^2+1/3\times(0.769J)^2+1/3\times(0.289J)^2}=0.788J=I_{db}=I_{dc}$. The voltage E_A being the same as for the 6-phase case above, the secondary kva $=0.408J(2\times 0.641+2\times 0.740)C=1.13GJ$, and the primary kva $=0.788J(0.641+0.740)\,G=1.09GJ$. The other circuit characteristics are the same as for the usual 12-phase case, and are given in Table II.

From the standpoint of spare transformers, it is desirable to have the two transformers interchangeable. To make them interchangeable it is only necessary to increase the number of primary turns on the teaser transformer to that of the main transformer. This increases the teaser primary voltage rating from $0.641G$ to $0.741G$ and the total primary kva rating to 1.17 as shown in Table II.

A 12-phase arrangement suitable for pool type rectifier tubes is also possible using four secondary T's. In this case the secondary kva is the same as the 3-phase case, 1.70; and the primary kva the same as the 12-phase above, 1.09.

The T connection can also be used for 2-phase supply, as shown for the 4-phase circuit in Table I, but the teaser transformer ratio will be different, and the transformer kva ratings slightly different.

III. Voltage Doubling Circuit

The voltage doubling circuit shown in Fig. 5, while hardly belonging under "polyphase rectification" is of interest since it is useful for single-

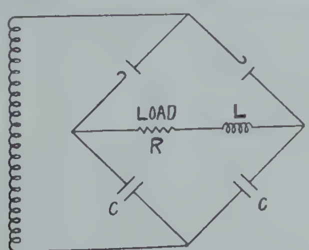


Figure 5. Diagram of voltage doubling circuit.

phase applications requiring such high voltages and small currents that it is not economical to build the transformers required for the usual single-phase rectifier circuit, and assuming that a condenser would be used on the output side of the rectifier. Also, it is an alternative for the single-phase bridge circuit where the rectifier tubes will not stand the

high inverse voltage of the half-wave or full-wave circuits. As can be seen, the voltage doubling circuit is like the single-phase bridge circuit except that the two rectifier tubes in the branches of the bridge connected to one end of the transformer are replaced by the two condensers, C. A study of the diagram shows that during one-half cycle, one of the condensers is charged to the full peak voltage of the transformer, and during the other half cycle the other condenser is charged to the full peak voltage. Since the two condensers are in series with each other with respect to the load, the no-load output voltage will be twice the transformer peak voltage. In comparison, the no-load output voltage with a condenser next the output side of the rectifier, is for the half wave circuit and the bridge circuit, equal to the transformer peak voltage, and for the full wave circuit equal to half the transformer whole secondary peak voltage. With condensers on the output, the peak inverse voltage on the tubes for the bridge and voltage doubling circuit is equal to the maximum output voltage, whereas for the half wave and full wave circuits it is twice the maximum output voltage.

In general, when condensers are used next the rectifier tubes on the output side the tubes will carry a large charging current for a small portion of the cycle, so that the peak anode current and transformer r.m.s. or effective current will be high compared to the d-c current. Also, the average d-c voltage will be somewhat less than the peak a-c voltage due to the discharge of the condensers between charging periods, so that the transformer secondary r.m.s. voltage will be more than 0.707/2 times the d-c voltage. To show how the load affects these quantities, they were calculated assuming a perfect transformer and rectifier, a sine wave supply, and the d-c current held constant as in the previous rectifier calculations, and that the peak tube current does not reach saturation, as shown in appendix A, for different values of the product of condenser capacity, and lead resistance. The values are shown by the curves of Fig. 6.

Examination of these curves shows that if the product CR is large the transformer secondary voltage approaches the value $0.354G$ where G is the d-c voltage, but that the transformer r.m.s. current may be several times the d-c current, J; and the peak anode current, many times J. For lower values of CR the transformer secondary voltage goes up and the transformer and peak anode currents decrease, though still being several times the d-c current. Transformer impedance will tend to spread the charging period out and so make the transformer voltage somewhat higher and the peak anode and transformer r.m.s. currents less than shown.

The voltage doubling circuit can be used with high vacuum tubes and hot cathode mercury vapor tubes, but not with the pool-type mercury vapor tube since separate cathodes are required. Single anode mercury pool-type tubes could, of course, be used, but might be unstable with a large condenser next their output. As with any rectifier using condensers on the output of hot cathode mercury vapor tubes, care must be taken to see that the peak anode current due to the charge of the condenser is not large enough to damage the filament.

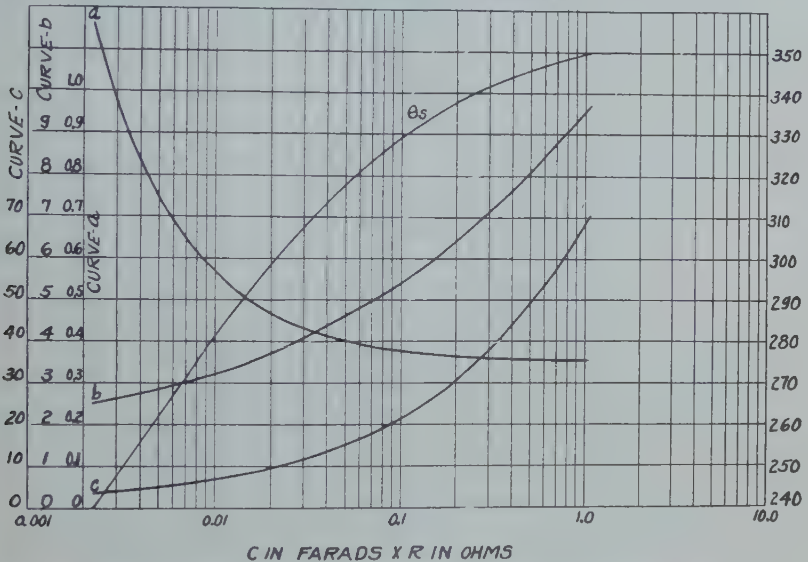


Fig. 6—Current and voltage relations of voltage doubling circuit. Curve a = transformer secondary r.m.s. voltage in terms of average d-c output voltage; curve b = transformer secondary r.m.s. current in terms of d-c output current; curve c = anode peak current in terms of d-c current. Transformer impedance and rectifier tube drop are neglected; it is assumed that supply voltage is sine wave, choke coil maintains d-c current constant, and peak tube current does not reach saturation.

It can be seen[4] that the secondary of the voltage doubling circuit functions like two half wave rectifiers of opposite phase and with condensers across their outputs in series, except that the single secondary transformer winding functions for both, and hence in both half cycles, thus avoiding a d-c component of flux in the iron. The transformer primary current for the voltage doubling circuit is the same as the secondary, but for the single phase half wave circuit, is the a-c component of the secondary current. Therefore, the data for the voltage doubling circuit can be adapted to the half wave circuit by multiplying the values of transformer r.m.s. voltage by 2, dividing the trans-

[4] See appendix A.

former secondary r.m.s. current by $\sqrt{2}$, and for the primary current, subtracting the d-c current component from the value obtained for the secondary, thus, primary current $= \sqrt{(\text{secondary current})^2 - J^2}$

Acknowledgments

The writer wishes to acknowledge his indebtedness to R. L. Davis and V. E. Trouant for suggestions and encouragement, and to Mr. Davis for suggesting the subject and for permission to use his material; and to L. R. Smith for checking some of the values in Table I.

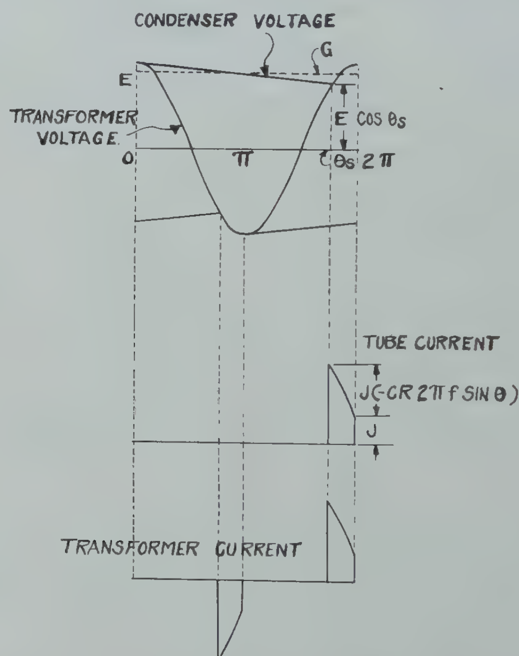


Fig. 7—Voltage and current wave forms of voltage doubling circuit assuming no reactance.

E = peak a-c voltage
G = average d-c voltage
j = d-c current
θ_s = phase angle at which condenser starts charging again.

Appendix A. Method of Calculation for the Voltage Doubling Circuit

In the calculation of the transformer r.m.s. voltage, the peak tube anode current, and the transformer r.m.s. current; transformer exciting current, resistance, and reactance, and tube voltage drop are neglected; and it is assumed that a choke coil in the d-c line maintains

the current constant, and that the peak tube current does not reach the saturation value.

Referring to the circuit diagram, Fig. 5, and the voltage and current wave forms, Fig. 7, consider, for the time being, one-half the system, i.e, the equivalent of a half-wave rectifier. Let the symbols be as follows:

e = instantaneous value of supply voltage = $\mathcal{E}\cos 2\pi ft$
$\mathcal{E}$ = peak value of sine wave voltage
f = frequency of supply voltage
q = instantaneous charge on condenser, C
C = capacity of condenser, C
J = d-c current
t = time measured from instant of maximum voltage $=\theta/2\pi f$
θ = phase angle of voltage vector
g = instantaneous rectifier output voltage
G = average d-c voltage
G' = average output voltage, C discharging
G'' = average output voltage, C charging
θ_s = phase angle at which condenser, C, starts recharging
i = instantaneous anode current
E' = r.m.s. a-c voltage of transformer for half wave rectifier
E = r.m.s. a-c voltage of transformer for voltage doubling circuit
$\mathfrak{J}$ = peak anode current
I' = r.m.s. transformer secondary current for half wave rectifier
I = r.m.s. transformer current for voltage doubling circuit
R = resistance of load

The condenser C is charged up to the peak a-c voltage at $\theta=0$, and immediately after, its voltage falls off due to discharge through the load so that

$$q = C\mathcal{E} - Jt \tag{1}$$

$$\text{and } g = q/C = \mathcal{E} - Jt/C = \mathcal{E} - J\theta/2\pi fC. \tag{2}$$

The voltage starts up again when $g=e$ or

$$\mathcal{E} - J\theta/2\pi fC = \mathcal{E}\cos\theta$$

$$\text{or } \theta = \theta_s \tag{3}$$

while condenser C is discharging the average value of the output voltage is

$$G' = (\mathcal{E} + \mathcal{E}\cos\theta_s)/2 \tag{4}$$

and while the condenser is charging it is

$$G'' = [1/(2\pi - \theta_s)]\int_{\theta_s}^{2\pi}\mathcal{E}\cos\theta d\theta = [\mathcal{E}/(2\pi - \theta_s)]\sin\theta\Big]_{\theta_s}^{2\pi} \tag{5}$$

The average over the complete cycle is

$$G = [\theta_s G' + (2\pi - \theta_s)G'']/2\pi. \tag{6}$$

The anode current, i, is zero until the condenser starts charging; then it equals the d-c current plus the current necessary to keep the condenser at the same potential as the anode for the period θ_s to 2π. (The assumption that the anode current ceases to flow at the instant the condenser is charged to the peak a-c voltage, i.e., at 2π, is an approximation under the initial assumptions, which is justified since neglect of reactance makes the values of the currents only rough approximations.)

$$\begin{aligned} i &= J + Cde/dt = J + Cd/dt(\mathcal{E} \cos 2\pi ft) \\ &= J - C\mathcal{E}2\pi f \sin 2\pi ft. \end{aligned} \tag{7}$$

The peak current is seen to be

$$\mathfrak{J} = J(1 - [C\mathcal{E}/J) \times 2\pi f \sin \theta_s) \tag{8}$$

except where θ_s is less than 270 deg., in which case

$$= J(1 - 2\pi fC\mathcal{E}/J). \tag{9}$$

The transformer r.m.s. current,

$$I = \sqrt{(1/2\pi) \int_0^{2\pi} i^2 d\theta}$$

and $i^2 = J^2 - 4C\mathcal{E}\pi fJ \sin\theta + 4C^2\mathcal{E}^2\pi^2 f^2 \sin^2\theta$

$$\begin{aligned} \text{so, } (1/2\pi)\int_0^{2\pi} i^2 d\theta &= (1/2\pi)\Big[\int_{\theta_s}^{2\pi} J^2 d\theta - 4C\mathcal{E}\pi fJ \int_0^{2\pi} \sin\theta d\theta \\ &\quad + 4C^2\mathcal{E}^2\pi^2 f^2 \int_0^{2\pi} \sin^2\theta d\theta\Big] \\ &= (1/2\pi)\big[J^2\theta + 4C\mathcal{E}\pi fJ\cos\theta + 4C^2\mathcal{E}^2\pi^2 f^2([\theta/2] \\ &\quad - [\sin 2\theta]/4)\big]_{\theta_s}^{2\pi} \\ &= (1/2\pi)\big[J^2(2\pi - \theta_s) + 4C\mathcal{E}\pi fJ(1 - \cos\theta_s) \\ &\quad + 2C^2\mathcal{E}^2\pi^2 f^2(2\pi - \theta_s) - C^2\mathcal{E}^2\pi^2 f^2(-\sin 2\theta_s)\big] \\ &= J^2\big[(2\pi - \theta_s)/2\pi + 2f(1 - \cos\theta_s)C\mathcal{E}/J \\ &\quad + \pi^2 f^2(2\pi - \theta_s)C^2\mathcal{E}^2/J^2 \\ &\quad - (\pi^2 f^2/2)(-\sin 2\theta_s)C^2\mathcal{E}^2/J^2\big]. \end{aligned}$$

Therefore

$$I' = J\sqrt{(2\pi - \theta_s)/2\pi + 2f(1 - \cos\theta_s)C\mathcal{E}/J + \pi^2 f^2(2\pi - \theta_s)C^2\mathcal{E}^2/J^2 - (\pi^2 f^2/2)(-\sin 2\theta_s)C^2\mathcal{E}^2/J^2}. \tag{10}$$

In the numerical calculation, θ_s was taken as the independent variable and $C\mathcal{E}/J$ determined from (3) letting $\theta = \theta_s$, thus,

$$C\mathcal{E}/J = \theta_s/2\pi f(1 - \cos\theta_s). \tag{11}$$

The transformer voltage, E', in terms of G is found from equation $E' = 0.707\mathcal{E}$, and the value of G in terms of $\mathcal{E}$ given by (4), (5), and (6).

The value of $\mathcal{E}$ in terms of G was obtained from (4), (5), and (6); and substituting this value in (11), the value of CG/J or CR was found for the different values of θ_s.

For the voltage doubling circuit, the peak anode current is equal to $\mathfrak{J}$, the transformer r.m.s. current, I, equal to $\sqrt{2}I'$ since the current flows in both half cycles, and the transformer voltage E, equal to $E'/2$ due to the voltage doubling action. The values were then plotted as a function of the product, CR, of the capacity of each condenser, C, and the load resistance R. The value of θ_s was also plotted since an indication of the ripple voltage can be obtained from it.

Appendix B. Conditions in a Transformer with a Resultant Direct-Current Component in the Secondary Winding

The existence of a d-c component of flux in the iron for the single phase half wave circuit and in the simple 3-phase star circuit was mentioned in Section I. A brief discussion of the phenomena seems appropriate.

Considering a half wave single phase rectifier as discussed in connection with the voltage doubling circuit, the transformer secondary voltage, secondary current, and primary current are shown in Fig. 8. The secondary current flows only in one direction due to the rectifier action, and therefore has a d-c component of current and an a-c component. Only the a-c part is reflected in the primary since a transformer cannot transfer direct current. If the d-c component is large compared to the normal exciting current, the iron will have a large d-c component of flux and will operate about a point, up on the flat part of the magnetization curve as shown at O' in Fig. 9, instead of about the origin, O. It can be seen that this greatly increases the necessary a-c excitation current, and the hysteresis loss.

At first thought, there might seem to be a discrepancy in the power in the stages of the transfer system, e.g., an excess of power in the

secondary winding over that in the primary, due to the presence of the d-c component. That this is not true, however, can be seen since there is no d-c component of voltage in the transformer secondary, and hence the d-c component of current does not represent additional

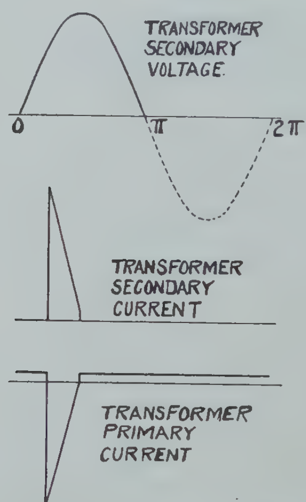


Fig. 8—Voltage and current waves of single-phase half wave rectifier with condenser across output.

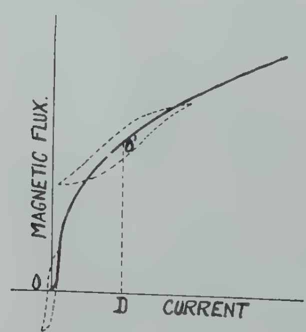


Fig. 9—Diagram showing shift of the operating point of the iron on the magnetization curve and increase of excitation current and hysteresis loss due to the resultant d-c component of current, *D*, in the secondary of a half wave rectifier transformer.

power. Between the rectifier tube and the condenser are the a-c and d-c components of both voltage and current but the a-c current is the charging current of the condenser, which is 90 deg. out of phase with the voltage as can be seen by comparison of the tube current and ripple voltage shown in Fig. 7. Likewise, in the rectifier output beyond the condenser and ahead of the d-c choke, assuming a perfect choke coil,

there is in addition to the d-c, an a-c component of voltage, but no a-c component of current; and on the load side of the d-c choke there is only the d-c voltage and current, so, though the power factor may differ in the several stages, the power, neglecting losses, is the same and equal to the d-c power.

The voltage and currents of the transformers for the 3-phase star circuit under the assumptions of Section I are shown in Fig. 10. The current in each secondary is equal to the d-c current for one-third the time and is zero the rest of the time. The primary current, equal

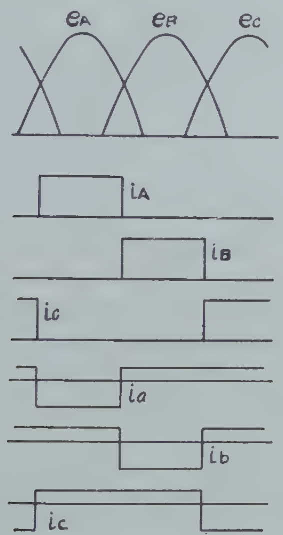


Fig. 10—Voltage and current waves of single phase transformers for the simple 3-phase star rectifier.

to the secondary current minus the d-c component, assuming a 1:1 ratio, is two-thirds the d-c current, for the one-third of the cycle in which the d-c current flows, and is one-third the d-c value in the opposite direction for the other two-thirds of the cycle. Here, as in other rectifiers, the rectifying action of the rectifier device produces the d-c component of the secondary current and tends to produce harmonics in the d-c output; and the d-c choke coil alternately stores up and releases the energy necessary to give a uniform d-c output, and generates the harmonic voltages which produce the harmonic currents necessary to give the flat-topped anode current wave.

Since conditions in the iron of a transformer for rectifier service with a resultant d-c component of current in the secondary, are similar to those in a transformer with d-c current in the primary, the same

design principles should apply, and an air gap in the magnetic circuit to prevent saturation of the iron should be desirable.

Bibliography

There has been less written on rectifier circuits than on the characteristics of the rectifying devices. The following works consulted deal directly with rectifier circuits.

1. W. Dällenbach and E. Gerecke, "Current and voltage conditions in the high capacity rectifier" ("Die Strom- und Spannungsverhältnisse der Grossgleichrichter"), *Archiv für Elektrotechnik*, **14,** No. 2, 171–246, 1924.

   This article is a thorough study of several of the most useful circuits for 3-phase supply including consideration of transformer reactance, current overlap of more than two phases, etc.

2. O. K. Marti, "Rectification of alternating currents," *Jour. A. I. E. E.*, **45,** No. 9, 832–846; September, 1926.

   This article, the theory of which is based on No. 1 above, shows concisely, the method of analysis of a rectifier circuit neglecting transformer impedance, and taking secondary reactance into account, and shows that using balance coils instead of a single multiphase star, reduces regulation due to transformer secondary reactance. The unabridged paper in the *A. I. E. E. Transactions*, May 26–28, 1926, with the discussion, gives a very complete bibliography.

3. D. C. Prince and F. B. Vogdes, "Principles of Mercury Arc Rectifiers and Their Circuits," 1927.

   This book describes various circuits and contains much material based on No. 1 above.

4. E. Gerecke, "Six-phase rectifier connections with single-phase transformers," ("Sechsphasengleichrichteranlage mit Einphasentransformatoren"), *Archiv für Elektrotechnik*, **19,** No. 4, 449–462; March 15, 1928.

   This paper considers the 6-phase star rectifier with 3-phase star primary and no tertiary winding, comparing it with similar circuits.

5. Meyer-Delius, "Best utilization of rectifiers and their transformers," ("Die Günstigste Ausnutzung von Gleichrichtern und ihren Transformatoren"), *Elektrizitätswirtschaft* (Berlin), **29,** No. 502, 77–83; February 2, 1930.

   This paper shows that the double 3-phase arrangement is better than other possible balance and choke coil combination of 6 phase.

6. L. B. W. Jolley, "Alternating Current Rectification", 1928.

   This book gives a good discussion of wave form analysis of rectifier currents.

7. A. Gunthershulse, "Electric Rectifiers and Valves", 1928.

   Translated and revised by Norman A. De Bruyne.

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NOTE ON SKIP DISTANCE EFFECTS ON SUPER-FREQUENCIES*

By

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During the last eighteen months the Naval Research Laboratory has made a very large number of measurements on skip distances in the frequency band between 30,000 and 40,000 kc. Most of the measurements have been taken during the month of January, February, and March, 1929, and the corresponding months of 1930. Since the measurements for the two succeeding years are substantially in agreement we believe it worth while to report them at the present time even though they are based largely on measurements made in a general southerly or southwesterly direction. A large number of different frequencies have been used in this band, most of the data being based on two-way communications. The experiments have naturally been restricted to the daylight hours.

The following table summarizes the results:

Frequency	Midday skip distance in nautical miles
20,000	800 miles
22,625	1100 "
26,000	1200 "
28,000	1400 "
32,000	1800 "
36,000	Greater than 1800 miles
40,000	Greater than 1800 miles

These figures are of course general averages of a very large number of observations. Suitable contacts were not available beyond 1800 miles and yet still within the first zone of reception, which permit a more accurate determination of the upper frequencies. As far as 40,000 kc is concerned only a small number of contacts were obtained on this frequency, so that it can be said in general that it is usually above the practical limit for long-distance communication.

It will be interesting to discuss briefly the normal type of variation during the day and the day-to-day variations from the general average. The general behavior of these frequencies was quite normal in that greater skip distances were always obtained in the forenoon and late afternoon, with the minimum skip distance from one hour

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to one and a half hours later than noon. This clearly indicates that the maximum ionization of the Kennelly-Heaviside layer occurs from one hour to one and a half hours after the sun passes the meridian. A very slight change in the electron concentration of the layer produces a great effect as far as these frequencies are concerned. They are indeed a very fine index as to small changes going on in the equivalent height of the layer. For instance, in the 20,000-kc band the skip distance at 0900 was frequently in excess of 900 miles. It is not possible, from the method of observation in this particular case, to say just how much in excess. In the late afternoon, after 1600, the same thing frequently occurs. This effect could be traced on all frequencies up to 36,000 kc, the very highest frequencies only being useable in the middle hours of the day.

As to the daily variations, they were of course quite considerable, indicating a variation of perhaps as much as 15 or 20 per cent under extreme conditions. Of course, the influence of magnetic storms was usually so great as to throw the entire table out by a very considerable amount, generally, however, having the effect of shortening the skip distance.

The transmitters used were between 500 watts and 1 kw in power and were sometimes used on doublets and sometimes on beam transmitters which concentrated the energy approximately within a cone 25 deg. in diameter. The concentration in the horizontal plane could be roughly determined by field measurements at a distance of one-half mile from the transmitter. This concentration closely approximated the theoretical value. The concentration in the vertical plane has not yet been definitely ascertained although a number of airplane flights have been made with a view of getting at this fact. Theoretically, it should be of the same order of magnitude as the concentration in the horizontal plane. No variation in the skip distance was observed when shifting from antenna to beam, which merely indicates that the general assumption that only low angle radiation is profitable on these frequencies is correct. Experiments were also made with beams horizontally and vertically polarized but no material difference in the skip distance effect was observed.

The general procedure in carrying out the tests was to establish two-way contact with a station and then to raise the frequency in small steps until the signals suddenly drop out. This point could be very satisfactorily determined and in fact, could generally be predicted somewhat in advance because the last frequency to come through would always have a tremendous intensity and the next higher frequency would then perhaps flicker in and out with very low signal

strength, or disappear altogether. This phenomenon was observed at both ends of the circuit.

Crystal-controlled transmitters were generally used for making the tests and a receiver using one radio-frequency amplifier stage, one detector stage, and two stages of audio amplification, was used on most of the receiving measurements. A great deal of data was also obtained from amateur stations and not much is known of the type of receivers they employed but it is likely that they used a detector with two stages of audio amplification.

There is reason to suspect that on these upper frequencies transmissions east and west differ quite radically from those north and south. However, within the first zone of reception (which would be inside of 2000 miles) there is no reason to suspect that there is a very radical departure from the skip distances given in the table. Naturally it has been difficult to pick observing stations properly to get this work in the east and west direction, so that observations are all too scanty to permit drawing very definite conclusions. Such observations as have been obtained show a fair degree of agreement with the observations obtained from the southwest and south.

When we come to the second zone of reception, however, which means the west coast and beyond in working westward, the situation is extremely complicated and will not be discussed in this paper. The north Atlantic circuits to Europe apparently also show much more complicated conditions than the southern circuits. This may be partly because the observations have to be made in the second and higher zones of reception, or it may be that the east and west transmissions are inherently different from the north and south.

Of course, it occasionally happens that somewhat abnormal conditions cause the 20,000-kc band to hang on well into the evening. Above 22,625 kc, however, there are very few, if any, instances of definite skip distance measurements; the point being no doubt that the number of electrons in the layer has thinned out to the point where these frequencies are no longer returned to the earth anywhere.

It may be mentioned in conclusion that a good many observations made on harmonics from high power, high-frequency stations in the 10,000-kc to 20,000-kc band have been used to check in with the other measurements and so far have been found to be in very fair agreement therewith. These harmonics indeed constitute a very serious annoyance many times in measurements in this field as they are of an astonishing intensity, in many cases stronger than the fundamental of the station in question as received in Washington.

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KENNELLY-HEAVISIDE LAYER STUDIES*

By

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Summary—*This paper describes progress in a recently inaugurated program of coöperative research for the study of radio transmission. Oscillographic observations of pulse transmissions made at the Bureau of Standards and Tufts College, in collaboration with workers at the Naval Research Laboratory and the Department of Terrestrial Magnetism, are discussed. Observations on 1410 kc and a number of higher frequencies are described, and oscillograms showing the complex phenomena frequently encountered in night transmission are shown. Evidence in support of the existence of several ionized strata, such as postulated by Appleton and Eckersley, is found, and examples of the pulse distortions frequently encountered in reflection or refraction are shown. The paper is presented merely as a preliminary report, and solicits the coöperation of others interested in observations of this type. The need of extended observations of varied types is emphasized, and a more extended quantitative discussion of results is reserved for a later communication when more data are available.*

I. Introduction

THIS paper is in the nature of a report on work in progress and an outline of proposed future investigations. During the last few years, studies of the phenomena of short time echoes as produced by the use of the pulse method have demonstrated quite conclusively the existence of a Kennelly-Heaviside layer (or layers) with distinct diurnal cycles in effective height. The importance of magnetic storm phenomena and marked seasonal changes has also been noted.

In order that the nature of these phenomena may be really understood and quantitative correlations established, however, it is necessary that consistent and extended observations be carried on over a considerable period of time and on varied frequencies.

Plans are now being completed for consistent observations at the Bureau of Standards and Tufts College in collaboration with observers at the Department of Terrestrial Magnetism and the Naval Research Laboratory. The coöperation of investigators located at other points is invited, for it is only by consistent observations over varied transmission paths that anything approaching a complete picture of the phenomena involved can be obtained. The contemplated program

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seeks to continue and expand the observational work on frequencies in the 4-megacycle region and also to include a number of other higher and lower frequencies. So far, the program has included observations in three frequency regions, but during the next few months transmission on a number of other frequencies is contemplated. A summary of some of the work which has thus far been carried out is given below.[1]

II. NKF Transmissions

Through the courtesy and cordial coöperation of the Naval Research Laboratory, it has been possible to continue observations of transmissions furnished by NKF, at the Department of Terrestrial Magnetism, the Bureau of Standards, and at Tufts College, on 4045 and 8650 kc. These observations have included several 24-hour schedules and also consistent observations on two days each week at the Bureau of Standards experimental station at Kensington on these frequencies.

The 24-hour tests have disclosed diurnal changes in layer height quite similar to those observed a year ago and already reported.[2] It is hoped that these observations may be continued at frequent intervals, and the seasonal characteristics indicated by previous observations further investigated. Also it is planned to conduct a more detailed investigation of pulse doubling and pulse distortion phenomena which seem frequently to be associated with the transmission. With this in view, an improved monitor has been installed to enable a careful check on the transmitted signals to be maintained and means of synchronization devised which will enable particular pulses to be observed at different points and the variability in their transmission over the various paths studied. We are awaiting more extended and continued observations before reporting the results of this work.

The consistent observations on 4045 and 8650 kc have indicated possible correlations with magnetic storms and sun spots and show clearly the anticipated relation of height to frequency as discussed by other observers.

The results of these observations are reported in another paper.[3] It is of interest to note that the observations reported in that paper (representing close-range daytime conditions) give, in general, simple patterns readily explicable by reflections from a few discrete and more

[1] Since this paper was written, observations have been made on a much larger number of frequencies.

[2] Kenrick and Jen, "Measurements of the height of the Kennelly-Heaviside layer," Proc. I.R.E., **17**, 711–733, April; **17**, 2034–2052, November, 1929.

[3] T. R. Gilliland, "Kennelly-Heaviside layer height observations on 4405 and 8650 kc," Forthcoming paper in the *Bureau of Standards Journal of Research* and this issue, Proceedings of the I. R. E., page 114.

or less sharply-defined boundaries. It will be noted that such a situation is in marked constrast to that observable in some of the other night tests reported in this paper, and, in fact, to nighttime observations on this same transmission with the Bureau of Standards set-up. Under such conditions extremely complex patterns are frequently observed; however, observations at low amplifications or gains usually disclose predominant peaks from which a rather consistent and ordered variation of predominant layer height may be deduced.[2,3]

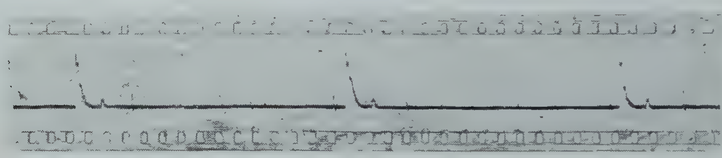

Fig. 1—1410-kc transmission as received at Tufts College on April 23, 1930 at 3:25 A.M., E.S.T. (High antenna employed.)

The 4045-kc signal strength from NKF in daylight does not permit satisfactory records to be made at Boston, and only single pulses have usually been observed on 8650 kc. At night signals of good intensity are usually observable on 4045 kc and the records obtained are frequently quite satisfactory, but the 8650-kc transmission fades out completely after passing through a sunset peak.

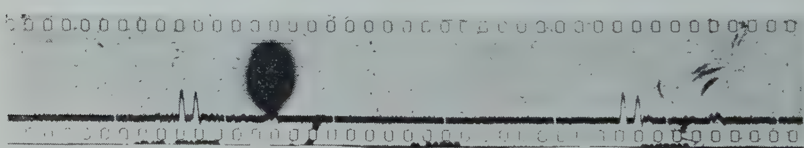

Fig. 2—1410-kc transmission as received at the Bureau of Standards experimental station at Kensington, Md., at 3:29 A.M., E.S.T. on April 23, 1930. (High antenna transmission.) Note retardations of 350 km and 2000 km.

III. Low-Frequency Transmissions

Recently early morning observations have been carried out on 1410 kc near the critical frequency region of Nichols and Schelleng. A large number of oscillograms resulting from these tests, as received at Tufts and at the Bureau of Standards, are available. Transmissions on this frequency were from Lexington, Mass. A few of the more interesting and characteristic effects observed are shown in the following figures.

At Boston (over a transmission path of only about 15 km) the ground wave was very powerful and the sky waves very weak when

[2,3] See footnotes 2 and 3.

a 3/8-wave vertical transmitting antenna of a type used to minimize high angle radiation in local coverage broadcasting was employed. Observations on this transmission, as received at Tufts, are shown in Fig. 1. Under similar conditions the Bureau observations gave quite satisfactory results. (See Fig. 2).

In order to secure high angle radiation and minimize the ground wave for local observations, a low half wave Hertz antenna was employed at the transmitter. This and the vertical antenna were used

Fig. 3—1410 kc as received at Tufts College at 2:50 A.M., April 23, 1930. (Hertz antenna employed.) Note relatively simple pattern (virtual height 370 km.)

alternately for half hour intervals. Much more satisfactory results were observable at Tufts when the Hertz antenna was employed. These observations are shown in Figs. 3 and 4.

In general it is found that the basic pulse phenomena are perhaps best studied at close range where a ground wave exists and where the reflections are at nearly perpendicular incidence. The patterns observable at longer distances indicate the complexity of the mechanism of long distance high-frequency transmission and the large number of

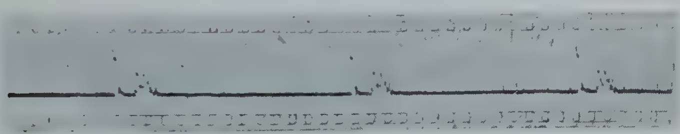

Fig. 4—1410-kc transmission as received at Tufts College at 3:33 A.M. Moderately high gain showing complex pattern. (Hertz antenna employed.)

paths that are frequently of importance. Visual observations of the patterns also indicate the rapidity of the fading encountered on the received signals from these various paths, and suggest the development of more refined methods, such as the use of directive antenna arrays, which will further disclose the mechanism involved.

The rapid variability of the patterns encountered is illustrated in Figs. 3 and 4. Fig. 3 is the pattern which sometimes corresponds to a moderate gain, while, under favorable conditions, increased gain produces complex patterns of the type shown in Fig. 4. Under such conditions inferences as to the effective height of the layer would seem-

ingly be precarious, if not indeed meaningless.[4] Patterns of the type of Fig. 4 are frequently evident on all the observed frequencies during night observations (usually corresponding to high sky wave energies), and may perhaps lead to some apprehension or skepticism as to what the significance of phase interference observations would be under such conditions.

In the case of observations with a long base line, the many possible paths render calculations other than those of equivalent path differ-

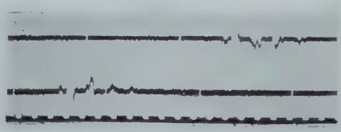

Fig. 5—Typical 1410-kc pattern as received at Kensington, Md., during night period, (3:33 A.M., April 13, 1930.) Note small peak, large peak, and then series of small peaks.

ences open to considerable question (particularly in view of results of the type shown in Fig. 4, which are quite typical). The long path difrence of 2000 km recorded in Fig. 2 is of particular interest in view of the low frequency. A typical type of record for the night pattern on 1410 kc, as observed at Washington, is shown in Fig. 5. It usually consists of a small peak followed by a larger peak and other smaller peaks of considerable retardation (although in general not as great as the 2000 km indicated in Fig. 2).

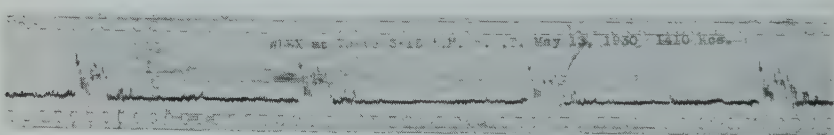

Fig. 6—1410 kc as received at Tufts College at 3:15 A.M., E.S.T., May 13, 1930. Note extremely complex dawn patterns.

Among the most interesting phenomena observable at Boston were two rather distinct layers during the sunrise period which could be observed to fade out separately. This phenomenon is indicated in Figs. 7 and 8.

In general it is difficult to generalize, as results obtained on one night may be quite different from those on another night, but perhaps

[4] In examining records, it should be noted that the input to the oscillograph was purposely and necessarily limited by tube saturation, and the recorded ordinates are hence not in linear relation. The ground wave, to a linear scale, would in many cases of high gain equal about 10 to 100 times the reflections (although much larger reflections are observable under favorable conditions).

a typical situation may be said to be a predominant low layer in the early night gradually disappearing (or rising) and disclosing a layer as indicated by Fig. 7, which again gives place to a low layer after dawn, as shown in Fig. 8. During the transition period both sets of

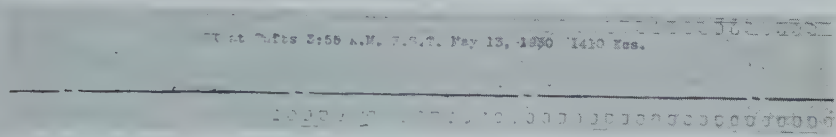

Fig. 7—Reception of 1410 kc at Tufts College on May 13, 1930, at 3:55 A.M., E.S.T. Note clear single reflection giving a virtual height of 310 km.

pulses may be observed to fade in and out and frequently appear simultaneously, as shown in Fig. 7. During the predawn period, extremely complicated patterns and evidence of extremely low layers are sometimes observable, as shown in Fig. 6.

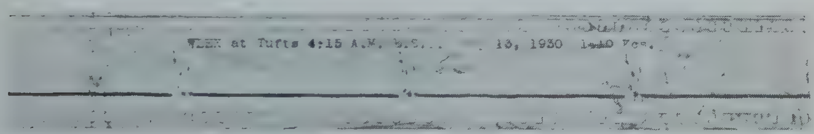

Fig. 8—1410 kc as received at Tufts College at 4:15 A.M., E.S.T., on May 13, 1930. Note appearance of 100-km layer with 300-km layer still visible.

After sunrise, the only indication of layers observable at Boston on 1410 kc during the spring tests of 1930 was the faint evidence of low layers shown in Fig. 9. At Washington, the patterns first degenerated into a simple pattern consisting of a single sharp peak similar to

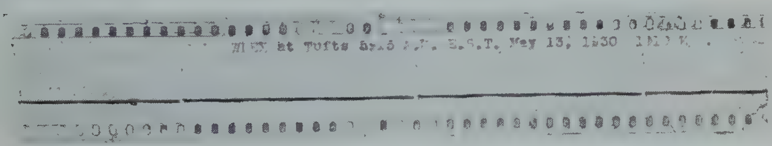

Fig. 9—Pattern after sunrise (5:15 A.M., E.S.T., May 13, 1930.) 1410-kc transmission. Note absence of reflections and clear single peaks due to ground wave.

that shown in Fig. 9, but the signals subsequently vanished altogether, attesting to the absence of the ground wave there. The peaks at Boston remain steady and single, as shown in Fig. 9, after daylight, confirming the fidelity of the transmission in the absence of sky waves. Without very careful monitoring at the transmitter (superior to that

obtainable with the cathode ray set-up employed), too much reliance cannot be placed in the very small secondary peaks of Fig. 9 which may have been introduced at the transmitter. However, they are strikingly like the results observed during the sunrise period on the spark transmission from WNW, reported in the Kenrick and Jen paper of last November.[5]

IV. Observations at Other Frequencies

Preliminary observations have also been conducted on 3256 and 6425 kc. The results of these observations are not yet available in sufficient quantity to render a general statement of results significant. Observations during April on 6425 kc indicated heights of the order of 400 km in the daytime and nighttime observations, in general, indicated an absence of reflections at normal incidence. A record taken at Tufts College at 11: 00 A.M. on May 2, 1930, is shown in Fig. 10.

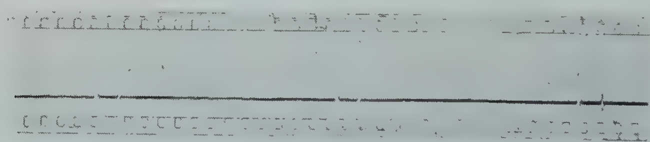

Fig. 10—Daytime record (11:00 A.M., E.S.T.) on 6425 kc as received at Tufts College. (Note 520-km virtual height indicated.)

No reflections were noted on other observations on this frequency at Tufts during the month of May. At Washington, several transmission paths of less path difference were consistently observed. A detailed description and analysis of the results of these tests (which are still in progress), and a more quantitative discussion of the results on 1410 kc, are reserved for another paper after more data have accumulated.

Heights of about 330 km indicated by some of the preliminary observations on 3256 kc mentioned here are in rough accord with the high layer heights mentioned by Appleton, while a lower layer sometimes observable in the daytime is somewhat greater in virtual height than his normal layer (due, perhaps, to the higher frequency).

V. Conclusions

The results of the observations described furnish considerable evidence for the existence of several layers, and support is thus given to the picture of Appleton and Eckersley of several rather definite strata.

[5] See footnote 2.

At Washington the results observed on the transmissions from Boston are naturally much more difficult to interpret because of the oblique transmission paths. Under such conditions, the complexity of the phenomena involved is, of course, enhanced by numerous multiple reflection effects. However, as will be noted, the observations at even short distances indicate phenomena sufficiently complex to tax the ingenuity of the investigator who would explain the phenomena by any more or less definite single layer, or even series of layers. Apparently it will be necessary, or at least highly desirable, to devise automatic methods which will allow extended and consistent observations before what may be said to constitute "typical" conditions or phenomena may be found. In fact, it appears that anything approaching a complete description will require much more than a statement of predominant effective heights of layer; it must also include layer turbulence and other causes of the complex pulse distortions observed. The immediate problem, however, seems to be to extend and continue consistent observations which will enhance the store of reliable data from which we may work, and at the same time seek other methods which will give us new and, let us hope, clearer insights into the nature of the pnenomena with which we are dealing. Other investigators interested in collaborating in this work are invited to communicate with the authors who will be pleased to furnish information concerning future schedules.

As stated at the outset, this paper is merely in the nature of a report of progress and an accumulation of data is awaited before an analytical discussion of the results is attempted.

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KENNELLY-HEAVISIDE LAYER HEIGHT OBSERVATIONS FOR 4045 KC AND 8650 KC*

By

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(Radio Section, Bureau of Standards, Washington, D.C.)

Summary—*Virtual heights of the Kennelly-Heaviside layer as measured by the radio echo method are reported for 4045 kc and 8650 kc. The report covers daytime observations made each week between January 16 and June 19, 1930. Two evening tests are also described. Curves are given comparing heights with sun spot numbers and magnetic character. Records taken on April 28, 1930, the day of the solar eclipse, are shown.*

THIS NOTE is a report of results obtained by the echo method in the study of the Kennelly-Heaviside layer between January 16 and June 19, 1930. The method used is essentially that first used by Breit and Tuve[1] and consists of the receiving and oscillographic recording of signals from a high powered transmitter which is sending out pulses or "peaks" of extremely short duration with sufficient intervals of no emission between pulses to record the echoes. The time interval between the arrival of the ground wave and the first echo is used to calculate the "virtual height."[2]

The transmissions were furnished through the courtesy of the Naval Research Laboratory at Bellevue, D. C. Two 20-kw crystal-controlled transmitters were used, one operating on 4045 kc and the other on 8650 kc, each being modulated by means of an unbalanced multivibrator circuit.[3] The records were made at the Bureau of Standards field station near Kensington, Md., at a distance of 21 km from the transmitter.

The results reported here were obtained from transmissions occurring each week on Mondays and Thursdays. The 4045-kc was transmitted from 11:15 to 11:30 A.M. and from 3:45 to 4:00 P.M., while the 8650-kc transmission was from 11:30 to 11:45 A.M. and from 4:00 to 4:15 P.M., E. S. T. On January 20 and 27 transmission was continued until midnight.

The curves in Fig. 1 show morning and afternoon virtual heights for both frequencies. The curves are plotted with straight lines through the observed points. Usually more than one record was obtained dur-

* Decimal classification: R113.61. Original manuscript received by the Institute, August 23, 1930. Publication approved by the Director of the Bureau of Standards of the U. S. Department of Commerce.

[1] G. Breit and M. A. Tuve, *Phys. Rev.*, **28**, 554; September, 1926.

[2] G. W. Kenrick and C. K. Jen, "Measurements of the height of the Kennelly-Heaviside layer," Proc. I. R. E., **17**, 711; April, 1929.

[3] M. A. Tuve and O. Dahl, Proc. I. R. E., **16**, 794; June 1928.

ing the fifteen minutes of transmission on each frequency, so that most of the points on the curves represent averages of several readings. Considerable changes in height have been noted within a few minutes.

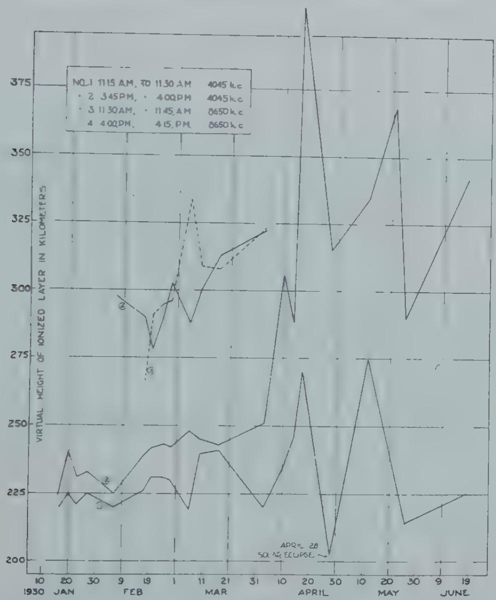

Fig. 1.

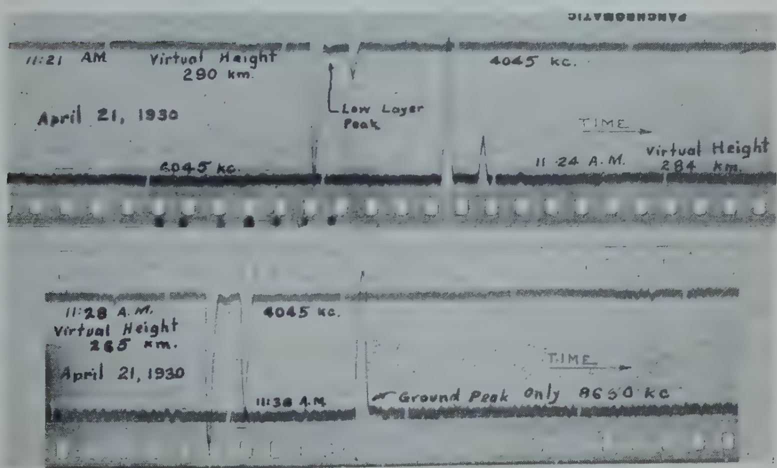

Fig. 2.

On the morning of April 21 a change from 290 km to 265 km was noted in seven minutes. (Fig. 2.) The interval between adjacent timing marks on each trace is 1/120 second. The curves of Fig. 1 show that

on 4045 kc the afternoon heights observed were always greater than the morning heights, but for 8650 kc this is not true. It is of interest to note that 8650-kc echoes were received only between February 6 and April 7. Except for this period, observations showed only the ground wave. During this time, however, the appearance of the echo pattern obtained on this frequency was usually similar to that for 4045 kc, except for the much greater retardation on the higher frequency. As many as five distinct echoes have been recorded from a single transmitted pulse. One peculiarity that has been noted at times in the pattern on both frequencies is the appearance of the last of a group of multiple echoes with greater amplitude than that of one or

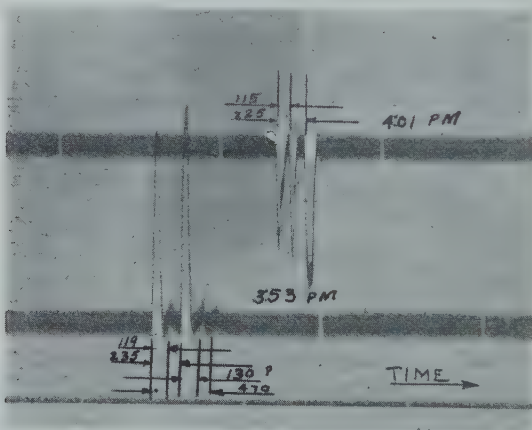

Fig. 3.

more of those preceding. Besides the layer for which the curves are drawn, a lower layer has been observed on 4045 kc on a few occasions, at a height of about 120 km. In Fig. 3 are shown two records taken on January 23. In the lower record a weak echo peak giving a height of approximately 119 km appears between the ground peak and the strong echo peak from the 235-km layer. Following the latter peak are two smaller ones, the first of which appears to be a multiple reflection from the low layer, and the second from the high layer. The upper record, taken eight minutes later, shows a much stronger reflection from the low layer. That multiples do not follow the reflection from the high layer may be attributed to the obscuring of the high layer by the lower one.

Records obtained on April 28, the day of the solar eclipse, give a morning height of only 202 km for 4045 kc, which is considerably lower than any other value obtained during this series of observations.

The lowest previous value was 219 km on January 16. The eclipse did not reach a maximum, which was 0.49 total, until 3:23 P.M. A record at 3:52 P.M. showed a height of 317 km. (Fig. 4.)

The curves of Fig. 5 were plotted to show possible correspondence which virtual heights might bear to sun spot numbers and to magnetic

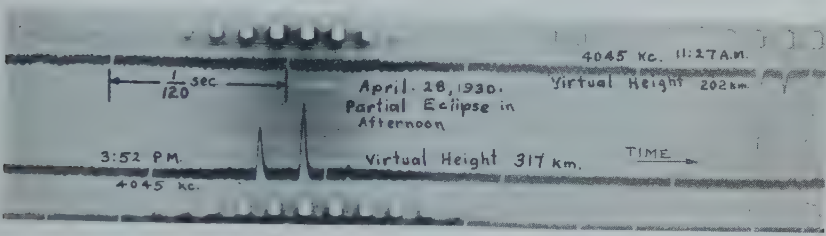

Fig. 4.

character. The curves of virtual height were plotted from averages of morning and afternoon values. The sun spot curve was plotted only for days on which measurements of height were made. Curve No. 1 shows the magnetic character of the day, zero representing a quiet day, while ordinates 1 and 2 represent moderate disturbance

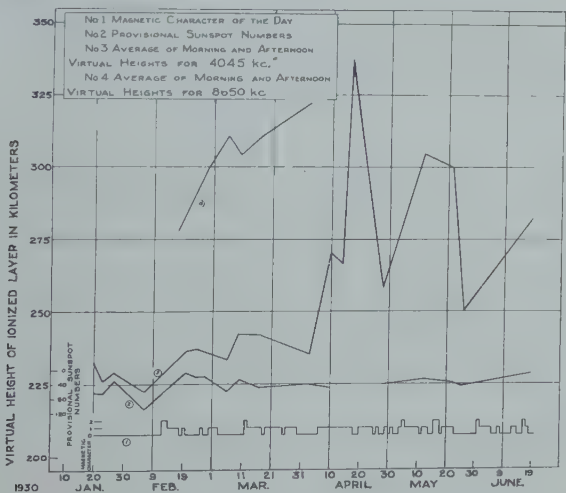

Fig. 5.

and severe disturbance, respectively. Although no conclusive correlation between magnetic character and height is evident from the curves, it will be noted that the disturbed period which began February 12 has been accompanied by a rise in height of considerable magnitude. The extreme heights (Fig. 6) beginning about April 10,

may suggest the disappearance of one layer, permitting a higher one to come into view rather than the rise indicated in the curves.

The existence of a close correspondence between sun spot numbers and virtual heights for 4045 kc, such as is suggested by curves 2 and 3, Fig. 5, can be demonstrated only by observations over a much longer

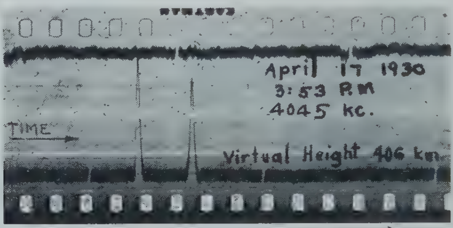

Fig. 6.

period. The correlation shown, while interesting, is not considered in any sense conclusive, because of the limited duration of the available observations.

The curves of Figs. 7 and 8 were plotted from data obtained when transmission was continued until midnight. In both cases heights are shown to fluctuate rapidly after dark. The dotted lines are drawn to indicate the possibility of the existence of two layers, both of which rise after dark. The curves would suggest that reflections are occurring

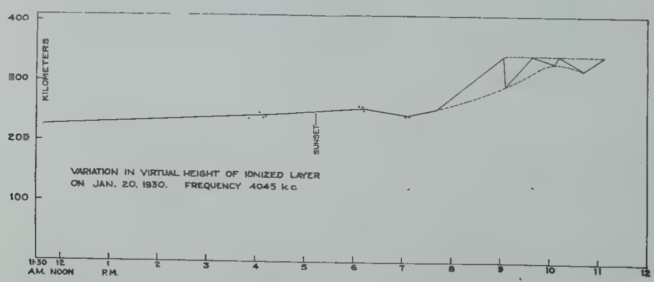

Fig. 7.

first from one layer and then from the other. Both of these evening tests show a dip after sunset, such as has been mentioned by other observers.

It will be noted that the curve for January 20 shows a maximum height of 344 km reached shortly after 9:00 P.M., while the curve for January 27 indicates no such "ceiling" but shows an increase up to 450 km at 11:41 P.M. It may be of interest to note that the provisional sun spot curve gives a value of 63 for January 20 and 31 for January 27.

Patterns obtained at night, especially during the early morning

hours, are, in general, not as simple nor as easily interpreted as those obtained in the daytime. The reflections frequently appear as a number of irregular peaks or form one broad pulse. To interpret such records in terms of one, or even several, well defined layers is extremely difficult. The results of such tests on other frequencies are reported in another paper recently published.[4]

During these observations it was not found practicable to monitor the transmitters to check the shape of the pulses sent out. In some cases the peaks were found to be split, but the character of the pat-

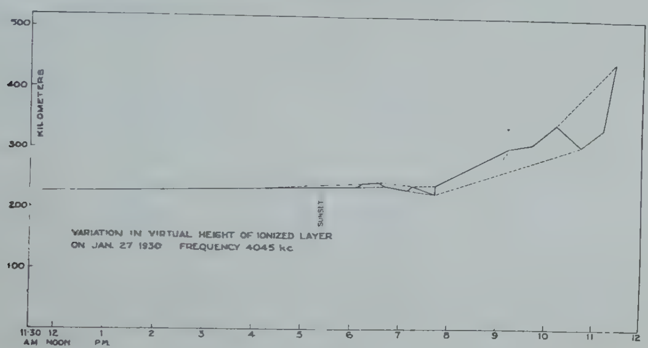

Fig. 8.

terns was such that no appreciable errors could be introduced in the measurement of virtual heights.

In view of the fact that these observations have been carried on for so short a period of time and for such limited conditions, no attempt is made to give an interpretation of the results at this time. It is hoped that observations may be continued over a longer period of time and for a number of other frequencies.

Thanks are due to A. H. Taylor and assistants at the Naval Research Laboratory for furnishing the transmissions, to the Department of Terrestrial Magnetism for sun spot data, and to the Coast and Geodetic Survey for magnetic data.

[4] P. A. deMars, T. R. Gilliland, and G. W. Kenrick, "Kennelly-Heaviside layer studies," Proc. I. R. E., this issue, page 106; *Bureau of Standards Journal of Research.*

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Volume 19, Number 1 *January, 1931*

THE DETECTION OF TWO MODULATED WAVES WHICH DIFFER SLIGHTLY IN CARRIER FREQUENCY*

By

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Summary—*The present paper contains an analysis of the detection of two waves modulated with the same, or with different, audio frequencies and differing in carrier frequency by several cycles or more. Both parabolic and straight line detectors are treated and there are derived the expressions for all of the important audio frequencies present in the output of these detectors when such waves are impressed. There are discussed the types of interference which result when one station is considerably weaker than the other and simple attenuation formulas are employed in estimating the character and extent of the interference areas around the two transmitters. Beyond the use of such formulas no attention is given to phenomena which may occur in the space medium such as fading, diurnal variations in field intensity, etc.*

WHENEVER one of two stations operating on the same wavelength assignment wanders from its proper frequency, waves are likely to be received which differ in carrier frequency by several cycles or more. Under such conditions the two signals may be thought of as made up of entirely distinct frequencies and phase relations between analogous components of the two waves need not be considered. In the important case in which the carriers are of identical frequency this is no longer true, and phase and its dependence on position and transmission phenomena must be taken into account. This case will be reserved for future study, the present work being limited to a consideration of the phenomena connected with the detection of distinct frequencies.

The most important undesired frequency which is present in the output of the detector is the beat note between the two carriers. It is sometimes carelessly assumed that if the frequency of this beat note is reduced below the audible range the only remaining interference will be due to the speech from the undesired station. Such is not the case and it will be shown later on that when the beat frequency is reduced below the audible range, but not to zero, there remains a group of spurious frequencies which will introduce an interfering background. When the undesired carrier is of relatively small intensity this background is a great deal stronger than the interfering speech. It is therefore desirable to obtain quantitative data on the interfering spectrum which occurs

* Decimal classification: R134×R170. Original manuscript received by the Institute, September 11, 1930.

in the receiver output, in terms of the intensities and degrees of modulation of the input signals.

It is to be expected that the results obtained will depend to some extent at least, on the type of detector which is used. The square law characteristic is a fair approximation to that of any detecting device which is worked over only a small range and hence an analysis of this characteristic may be expected to serve as an excellent guide to general detector performance. When large signals are impressed on the detector the functioning of the device may approximate more closely to that of the ideal straight line detector. It has been felt that a study of these two types would furnish data from which the performance of any intermediate type of detector could be inferred without great error. As the problem of the square law detector is very much the simpler it will be considered first.

Mathematical Analysis

There will be assumed two broadcast stations transmitting on frequencies which differ by a relatively small amount, the beat frequency being restricted to the audible range or less. Each of the carriers will be assumed to be modulated by a single audio frequency, the modulating frequencies at the two stations being, in general, different. The total signal impressed on the receiving detector will then be of the form;

$$v = E(1 + M \cos pt) \cos \omega_1 t + e(1 + m \cos qt) \cos \omega_2 t. \qquad (1)$$

In which

v is the total alternating voltage impressed on the detector.
E is the amplitude of the desired carrier
e is the amplitude of the undesired carrier
M is the degree of modulation of the desired signal
m is the degree of modulation of the undesired signal
$\omega_1/2\pi$ is the frequency of the desired carrier
$\omega_2/2\pi$ is the frequency of the undesired carrier
$p/2\pi$ is the frequency of the desired modulation
$q/2\pi$ is the frequency of the undesired modulation

Square Law Detector

We shall first suppose this signal to be impressed on a detector which will be assumed to have a characteristic in the neighborhood of the operating point, of the form

$$i = A_0 + A_1 v + A_2 v^2. \qquad (2)$$

An expression of this type will accurately represent a small portion of any continuous characteristic. The present analysis requires that the

impressed e.m.f. shall be of small amplitude in order that the limits of the portion of the characteristic thus represented may not be exceeded. This restriction is necessary in treating square law detectors.

The audio-frequency output of the detector will be due entirely to the second order term in (2). Hence it will be sufficient, for our purposes, to square the expression for v. We are interested primarily in the ratios of the amplitudes of the various undesired audio frequencies produced to the amplitude of the desired signal of frequency $p/2\pi$. Such a ratio will be designated as a relative amplitude. Neglecting circuit constants, etc., which will apply equally in all the expressions for the various frequencies, the amplitude of the desired component of the audio-frequency output is readily shown to be E^2M. The expression for v^2 is reduced to first power sinusoids and the amplitude of each frequency converted to a relative amplitude by dividing by E^2M. The case in hand yields twelve undesired audio frequencies, the relative amplitudes of which are listed in Table I. Before commenting on these results we shall consider the straight line detector.

TABLE I

Angular Velocity	Ratio to E^2M	Angular Velocity	Ratio to E^2M
$2p$	$\dfrac{M}{4}$	$p \pm u$	$\dfrac{e}{2E}$
q	$\dfrac{e^2m}{E^2M}$	$q \pm u$	$\dfrac{em}{2EM}$
$2q$	$\dfrac{e^2m^2}{4E^2M}$	$p \pm q \pm u$	$\dfrac{em}{4E}$
u	$\dfrac{e}{EM}$		

in which $u = \omega_1 - \omega_2$

The Straight Line Detector

In making analyses of rectification by a straight line detector it is customary to reduce the sum of the various impressed radio frequencies to a single radio frequency, the amplitude and phase angle of which are slow functions of time. The most common example of this type of treatment is a combination of the carrier and two side bands of single frequency modulation into the familiar expression for a modulated wave in which the amplitude of the radio frequency is an audio-frequency function. In this case the radio-frequency phase angle is constant. In the case of a single frequency modulation with one side band eliminated there are impressed on the detector input only two

frequencies. These may be combined in a well known manner.[1] Thus if the impressed voltages are of the form $a \cos x$ and $b \cos y$ then the amplitude is given by

$$\sqrt{a^2 + b^2 + 2ab \cos (x - y)}. \tag{3}$$

The expression for the phase angle will not be given here as it can be shown that if a and b are unequal and the difference between the frequencies $x/2\pi$ and $y/2\pi$ is small compared with either frequency, then the variation of the phase angle with time may be neglected in computing the audio-frequency components. In the present case we have two radio-frequency waves the amplitudes of which are not constants but are slow functions of time and these may be substituted for a and b in (3). Thus the effective amplitude of the total input signal may be taken to be

$$S = \sqrt{A^2 + B^2 + 2AB \cos ut} \tag{4}$$

in which $A = E(1 + M \cos pt)$

$B = e(1 + m \cos qt)$ and

$u = \omega_1 - \omega_2.$

The problem then resolves itself into an analysis of the detection, by a straight line detector, of a single radio-frequency component. The results of such an analysis are well known and it can be readily shown that the audio-frequency output may be obtained, except for a factor of proportionality, by resolving the amplitude into its audio-frequency components. In the present case the amplitude to be resolved is given by (4) which may be written

$$S = \sqrt{(A + B)^2 - 2AB(1 - \cos ut)}.$$

The interfering signal B, will be taken to be always less than the desired signal A, and hence $A^2 + B^2 > 2AB$ from which it follows the $(A+B)^2 > 2AB\ (1 - \cos ut)$. Hence the radical may be expanded by the binomial theorem giving

$$S = A + B - \frac{AB(1-\cos ut)}{A+B} - \frac{A^2B^2(1-\cos ut)^2}{2(A+B)^3} - \frac{A^3B^3(1-\cos ut)^3}{2(A+B)^5} \cdots \tag{5}$$

It is to be observed that each of the terms of this series, except the first, contains time in the denominator and hence further expansions are necessary. The denominators of the various terms can be expanded

[1] Lord Rayleigh, "Theory of Sound." Page 23, sec. ed.

by the binomial theorem in such a way as to put all the expressions containing time in the numerators, the expansions being in powers of

$$(ME \cos pt + me \cos qt)/(E + e).$$

By the proper trigonometric transformations it is possible to reduce the final expression for S to frequencies in p, q, u, and the sums and differences of the various multiples of these quantities. An additional discussion of this analysis is given in an appendix. In order that the various series involved may converge with a manageable degree of rapidity it is necessary to limit the relative amplitudes of the interfering carriers and the degrees of modulation as well. Consequently the solutions are restricted to intensities of the interfering carrier of 0.1, or less, of the desired carrier and to degrees of modulation of either signal ranging from 0.1 to 0.5. These limits are suitable also because we are interested chiefly in interference by a relatively weak signal, since the interference caused by a signal, the carrier amplitude of which is greater than 0.1 that of the desired carrier amplitude is near the tolerable limit in the majority of cases. The upper value for the modulation of 0.5 is approximately equal to the average degree of modulation of a station employing as deep modulation as is practical, only the peaks running up to nearly unity. The value of 0.1 for the lower limit is of course transgressed by soft passages in speech or music. However, the range here specified is sufficiently large to give an excellent idea of what may be expected from various degrees of modulation of desired and interfering signals and the results of more extreme cases may be inferred from the data here developed. Under these limits it is found that the only audio frequencies of any importance which appear in the output are:

$$\begin{aligned} S = {} & \left(ME - eg\left[a_0M - a_1 + a_2\frac{M}{2}\right] + \frac{m^2e^2Mg^2}{2E}\right) \cos pt \\ & + \left(me - eg\left[a_0m - \frac{a_1Mm}{2} - \frac{meg}{E}\right] - \frac{3e^2g^3b_0m}{2E}\right) \cos qt \\ & + \left(\frac{m^2e^2g^2}{2E} - \frac{b_0e^2g^3m^2}{4E}\right) \cos 2qt \\ & + \left(eg\left[a_0 - \frac{a_1M}{2} - \frac{m^2eg}{2E}\right] + \frac{b_0e^2g^3}{2E}(2 + m^2)\right) \cos ut \\ & - \frac{b_0e^2g^3}{4E} \cos 2ut \end{aligned}$$

$$+ \, eg\left(\frac{a_0M}{2} - \frac{a_1}{2} + \frac{a_2M}{4} - \frac{m^2Meg}{4E}\right)\cos\,(p \pm u)t$$

$$+ \left(eg\left[\frac{a_0m}{2} - \frac{a_1Mm}{4} - \frac{meg}{2E}\right] + \frac{b_0e^2g^3m}{E}\right)\cos\,(q \pm u)t. \tag{7}$$

In which

$$\left.\begin{aligned} a_0 &= 1 + \frac{M^2g^2}{2} + \frac{3M^4g^4}{8} \qquad & a_1 &= Mg + \frac{3M^3g^3}{4} + \frac{5M^5g^5}{8} \\ a_2 &= \frac{M^2g^2}{2} + \frac{M^4g^4}{2} & b_0 &= 1 + 3M^2g^2 \\ g &= \frac{E}{E+e}. \end{aligned}\right\} \tag{7a}$$

Comparison Between Detectors

It is now possible to make a comparison between the performance of the straight line and the square law detectors. In Figs. 1 to 4 are shown the relative amplitudes of the interfering frequencies in the two cases for various degrees of modulation. The data for the square law case are indicated by dashed lines and for the straight line case by solid lines, and where the two coincide this is noted on the figures. It is to be noted that the expression for the amplitude of the desired frequency $p/2\pi$ is a complicated function. However, computation shows that over the range in which we are interested, the value of this expression does not differ from ME by more than 1 per cent and therefore, this value has been assumed in computing the relative amplitudes of the other frequencies.

Probably the most striking feature to be noted in comparing the two cases is the similarity of the results. This is particularly evidenced by the carrier beat note of frequency $u/2\pi$ the amplitude of which differs in the two cases by an inappreciable amount. The spurious frequencies $(q \pm u)/2\pi$ also are practically identical for both detectors. There are, however, several important differences as follows:

The group of spurious frequencies of angular velocity $p \pm q \pm u$, which is of appreciable importance in the square law case, is entirely absent from the range of magnitude considered when a straight line detector is employed. The frequencies $(p \pm u)/2\pi$ are greater in the square law case over the range which we have considered, but the curve which represents them has a smaller slope than in the straight line case and for larger values of the interfering signal the intensities

of these frequencies would be relatively less with the square law detector. The intensity of the undesired speech q is definitely less in the straight line case than in the square law case but the slope of the q curves is about the same for both except for $M=m=0.5$. It is of interest to observe that the interfering speech received on the straight line detector is very much less in intensity than would be the case if the strong desired signal were absent, and that the variation of the

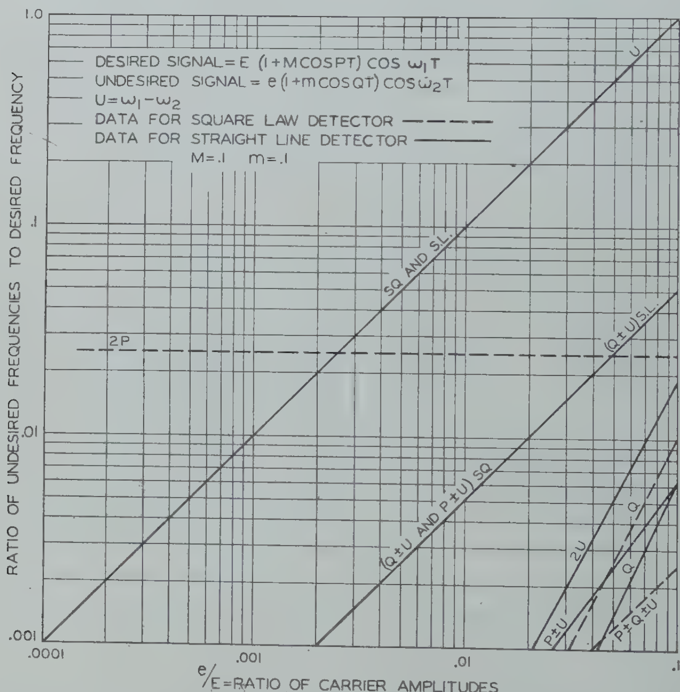

Fig. 1—Relative amplitudes of undesired frequencies as a function of the ratio of the amplitudes of the desired and the interfering carriers. Modulation of both stations small and equal.

amplitude of this frequency with intensity of the undesired carrier is greater when the desired frequency is present. We have here an analytical description of the familiar masking effect which occurs when a strong unmodulated carrier is received simultaneously with a weak modulated signal. For example, when $e/E=0.1$ it can be seen from curve 1 that the relative amplitude of the component of frequency $q/2\pi$ is 0.0063 for the case of the straight line detector. If this component were unaffected by the presence of the strong signal it would have an amplitude proportional to em and a relative amplitude of

em/EM which for the values here considered is 0.1. Hence the "masking" effect is here responsble for a reduction of 24 db.

Lastly, it may be mentioned that there are in the case of the straight line detector certain frequencies of small amplitude which are entirely absent from the square law case. However, no frequency is shown the relative amplitude of which is less than 0.01 for all four pairs of values of M and m, as such frequencies are unimportant. An

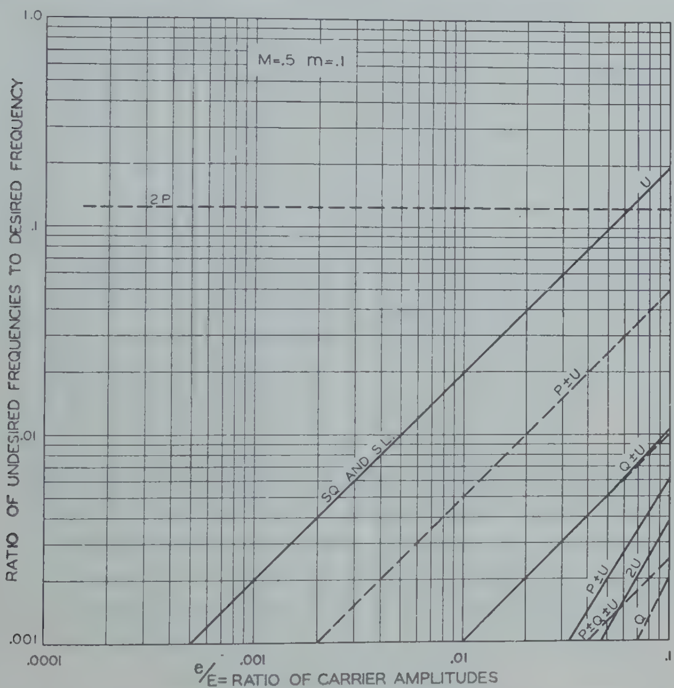

Fig. 2—Relative amplitudes of undesired frequencies as a function of the ratio of the amplitudes of the desired and the interfering carriers. Modulation of desired station small and of interfering station large.

exception is made with regard to $p \pm u$. This is always less than 0.01 over the range considered but is included for the sake of comparison with the square law results.

Further Consideration of Detector Output

The second harmonic of the desired signal is of importance only in the square law case. It is of the nature of a distortion which is independent of the interference and may be omitted from the consideration of the undesired audio frequencies which are a result of the interference. From Figs. 1 to 4 it is evident that the most important

interfering frequencies are those of angular velocity, u, $q \pm u$, $p \pm u$, and $p \pm q \pm u$, the last being of importance only in the case of the square law detector. It is with these frequencies, together with that of the interfering speech $q/2\pi$, that we shall be chiefly concerned.

When the relative magnitudes of the interfering frequencies, which are tabulated on page 123, are multiplied by E^2M the resulting quantities are proportional to the absolute magnitudes of these frequencies. It is to be noted that the frequencies of greatest interest have absolute

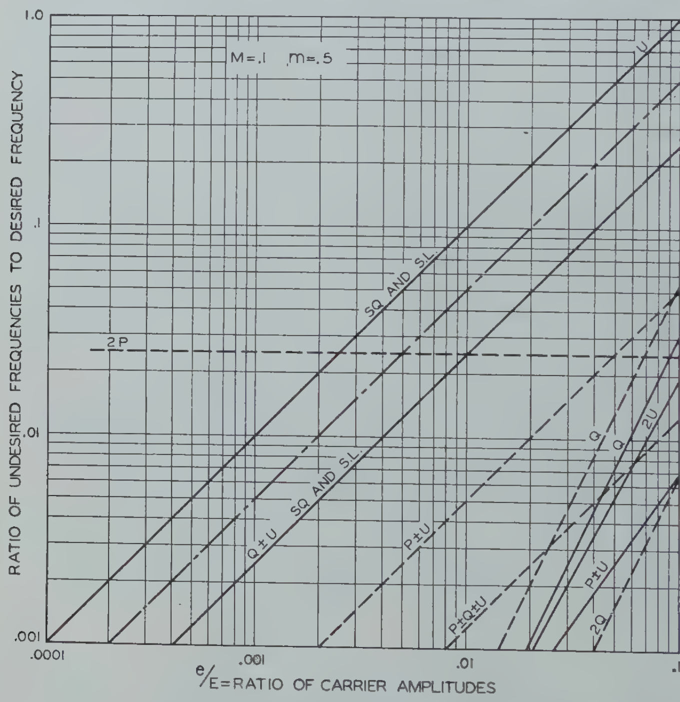

Fig. 3—Relative amplitudes of undesired frequencies as a function of the ratio of the amplitudes of the desired and the interfering carriers. Modulation of desired station large and of interfering station small.

magnitudes which are linear functions of M or m except $(p \pm q \pm u)/2\pi$ which is proportional to mM, and $u/2\pi$ which is independent of both M and m and will therefore, be uneffected by the type of modulation employed at either station. In case there are several frequencies present in the modulation of each station the radio-frequency waves will be of the form $E(1+M_1 \cos p_1t+M_2 \cos p_2t+ \cdots) \cos \omega_1 t$ and $e(1+m_1 \cos q_1t+m_2 \cos q_2t+ \cdots) \cos \omega_2 t$. For every frequency of the former case which contained M as a factor of its amplitude we shall now have several frequencies respectively proportional to M_1,

M_2, etc., while an analogous new group will correspond to the former frequencies containing m. Hence we shall have two frequency spectra derived from the desired speech spectrum containing the p's, but one of the spectra will be shifted upward in frequency by an amount $u/2\pi$ and the other downward by the same amount. Two additional spectra will be derived in a similar manner from the undesired speech spectrum containing the q's. The frequencies of the type $(p \pm q \pm u)/2\pi$ will be numerous as there will be a product of the M's with each of the m's.

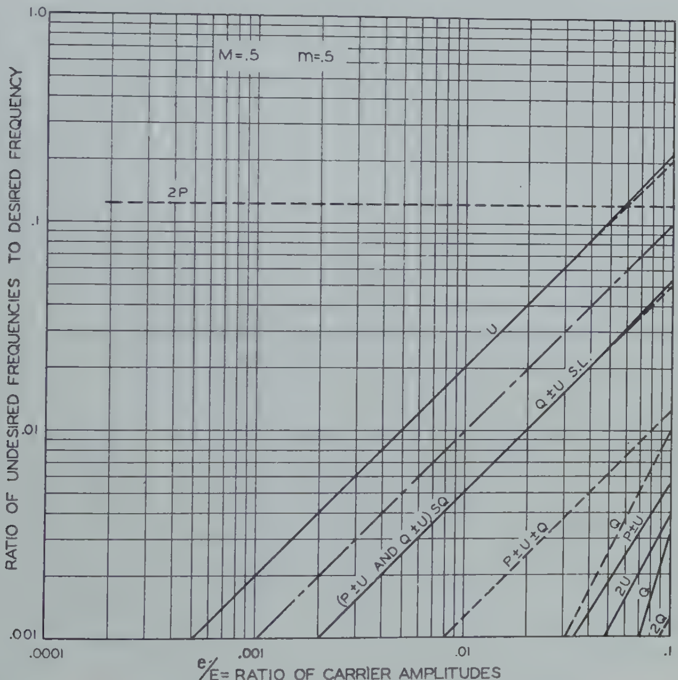

Fig. 4—Relative amplitudes of undesired frequencies as a function of the ratio of the amplitudes of the desired and the interfering carriers. Modulation of both stations large and equal.

However, these are of even moderate importance only when the modulations of both stations are high, and a square law detector is employed at the receiver.

Hence we may picture the interference as made up chiefly of displaced frequency spectra of the type mentioned above, of a carrier beat and of the interfering speech, which is weak but important because of its intelligibility. The results in the case of a straight line detector would not be very greatly different. The frequencies of the type $(p \pm q \pm u)/2\pi$ would be negligible, the two spectra derived from $p \pm u$

would be much less important, and certain new but rather small cross-product frequencies would appear.

In estimating the interference the carrier beat can be considered by itself and from the data at hand there can be derived the areas around each of two stations having approximately the same carrier frequency, inside of which the amplitude of the beat note will be down a given number of db from that of the desired speech. The same is true of the interfering speech when it is different from the desired speech. The frequencies $(p \pm u)/2\pi$, $(q \pm u)/2\pi$, $(p \pm q \pm u)/2\pi$, etc. will combine to form a disturbing background which we shall designate as "displaced side band interference." This may be taken to include all of the interfering frequencies except those of the undesired speech and its entirely unimportant harmonics. (The frequency $2p/2\pi$ is not here classed as an interfering frequency.)

From Figs. 1 and 4 it is to be noted that when $m = M$ the frequencies $(q \pm u)/2\pi$ are the largest components of the displaced side band interference if a straight line detector is used and have the same amplitude as the $(p \pm u)/2\pi$ components if a square law detector is used. When $m > M$ the $q \pm u$ group is much more important than the $p \pm u$ group as is evident from Fig. 2. When $M > m$ the $q \pm u$ group is less important but this case is of no great interest for if the stations are transmitting identical programs, with similar degrees of modulation, it cannot occur and if the programs are different then the interference is determined primarily by what happens when $m > M$. Consequently we may consider that the $q \pm u$ group constitutes the most important part of the displaced side band interference except when a square law detector is used and the programs are identical. In such a case we shall assume that both stations employ the same degree of modulation and that therefore the $q \pm u$ and $p \pm u$ groups are of the same importance.

Interference Areas of Stations

We have distinguished between three types of interference, namely, carrier beat, unwanted speech, and displaced side band. We shall now compute, for several values of attenuation, percentage modulation etc., the areas around a transmitting station inside of which each of these types of interference, due to a second station, will have a relative importance which is not greater than a certain specified amount.

In estimating these areas we must deal with two possible cases which may arise in practice: (1) The two stations transmit different programs. (2) The programs are the same. The carriers are assumed to differ in frequency in both cases.

Case 1

The importance of the various types of interference which are present, will be determined by their ratios to the intensity of the desired speech. In the present case in which the two stations transmit different programs, the amount of interference which may be tolerable will be determined by what occurs when the modulation of the desired station is low, while that of the interfering station is high. Hence in studying this case we shall make use of Fig. 2 which gives data computed on the basis of a modulation of 0.1 for the desired station and 0.5 for the interfering station.

Taking up first the consideration of the carrier beat note, we shall determine the curve along which the intensity of the beat is down a given number of db from the desired speech. The position of this curve will depend on the degree of modulation of the desired signal, since the lower the modulation the more noticeable will be a beat note of a given intensity. When we have specified the db difference which must exist between these two components of the receiver output the carrier ratio can be picked off from the u line of Fig. 2.

In order to determine the curve along which this carrier ratio exists we shall proceed as follows:

The desired station will be considered to be at the origin of a system of rectangular coördinates and the undesired station will be at the point (D, O). We shall assume that the powers of the desired and undesired stations are P_1 and P_2, respectively, and that their distances from a point in the coördinate plane are d_1 and d_2, then if we denote the ratio of the carriers by $K = e/E$ the equation of the curve along which the value of K is constant is given by:

$$\frac{K\sqrt{P_1}}{d_1}\epsilon^{-gd_1} = \frac{\sqrt{P_2}}{d_2}\epsilon^{-gd_2}. \tag{8}$$

This equation is based upon a convenient form of the Austin-Cohen[2] formula for the intensity of the field radiated from a radio transmitter. This formula is:

$$E = A\epsilon^{-101.5\alpha d/\lambda^{0.6}} \tag{9}$$

in which λ is the wavelength in meters, d is the distance from the transmitter in miles and α is an attenuation constant which may range from zero up to 0.01 or even more. In writing down (8) we have used the abbreviation:

$$g = \frac{101.5\alpha d}{\lambda^{0.6}}. \tag{10}$$

[2] L. W. Austin, Proc. I. R. E., 14, 377; June, 1926.

From (8) there have been computed curves for the case in which $P_1 = P_2$ and for various values of K and α. λ has been taken as 300 meters and D, the distance between the stations as 1000 miles.

In Fig. 5, are shown several curves for $\alpha = 0.001$. For small values of K, the curves are practically circular and are of small area. As K increases, the curves become oval shaped and it can be readily shown that for values of K greater than a certain critical amount, the curves will not close but will be of a shape which is roughly hyperbolic.

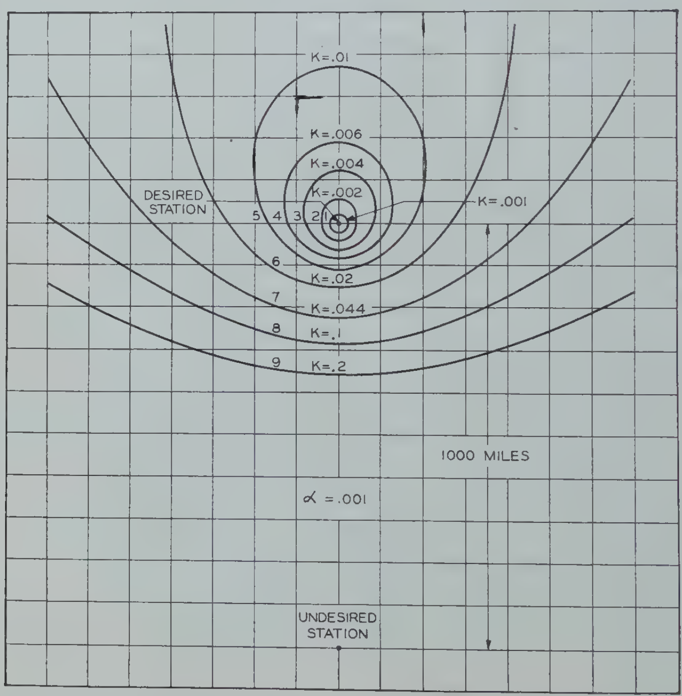

Fig. 5—Curves along which the ratio of the carrier amplitudes received from two stations has a constant value K, as indicated. Attenuation small.

In Fig. 6, are shown curves corresponding to a value for α of 0.002. It is to be noted that an increase in α, enormously increases the area inside of which the ratio of the carriers is less than a certain value. The effect of α will of course be dependent upon the magnitude of the distance between the stations and will be more pronounced the larger this distance. For the present case in which $D = 1000$ miles, there is not much point in considering values of α larger than 0.002, since the attenuation would be so great as to make the effect of one station on the service area of the other of very little consequence.

If we specify that the carrier beat must be at least 40 db down from

the speech output due to a 10 per cent modulated signal then curve 1 of Figs. 5 and 6 will represent the areas inside of which this requirement will be met, while if we call for an interval of 20 db between these two components, curve 5 of Figs. 5 and 6 will represent the areas in which the condition is satisfied. It is evident that if a rigid restriction is placed on the permissible beat note interference which may be allowed, and if the attenuation is of a small value then the area in which

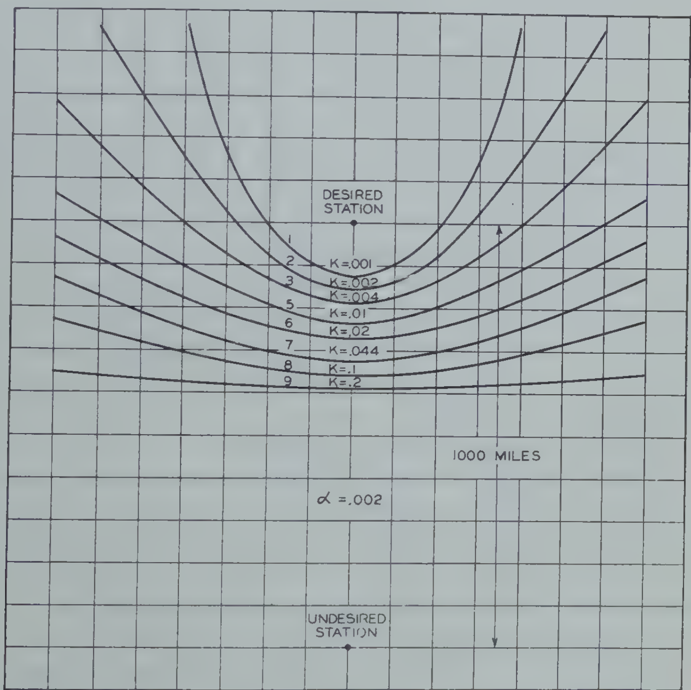

Fig. 6—Relative amplitudes of undesired frequencies as a function of the ratio of the amplitudes of the desired and the interfering carriers. Attenuation constant twice that of Fig. 5.

the beat note may be neglected is extremely small. On the other hand this area increases very rapidly as the attenuation increases.

We may use the same sets of curves in considering the displaced side band interference. From Fig. 2 it is evident that by far the most important components of this interference are those represented by the $q \pm u$ group. In order to estimate this interference we must follow some rule for combining the $q+u$ component with the $q-u$ component. In order to do this in a strictly correct manner we should have to take into account the frequencies and sensation levels of the

components. However, it has been shown[3] that over a considerable portion of the audio-frequency range, and for sensation levels of approximately the magnitude in which we are interested, the interfering effect of these frequencies may be taken to be approximately equal to that due to a single frequency of twice the amplitude of either component. We shall therefore take our data from the dash-dot curve of Fig. 2. From this curve it appears that if the displaced side band interference is to be 40 db down from the desired speech, we must have a carrier ratio of 0.002, while if it is to be 20 db down from the desired speech the corresponding carrier ratio is 0.02. The curves corresponding to these values are shown by 2 and 6, respectively, on Figs. 5 and 6.

From this it appears that the area in which the side band noise is not objectionable may be a great deal larger than that in which the carrier beat is of a tolerable intensity. If the frequency of the carrier beat is reduced below the useful audible range then the former area may be considered to be entirely free from interference of any kind. Consequently, it is highly desirable to limit the maximum possible differences in the carrier frequencies to a value which is definitely below the audio-frequency pass band of commercial radio receivers and loudspeakers.

Turning now to the undesired speech, we note that it is of very little importance compared with the displaced side band interference. Thus, if this speech is to be 40 db down from the desired speech, the value of the carrier ratio is 0.044 for the case of a square law detector, while for a difference in level of 20 db, the carrier ratio is 0.14. A curve for the case of a 40 db difference is indicated by 7 of Fig. 5.

The comparison between curves 7 and 6 emphasizes the fact that we may have considerable areas of intolerable displaced side band interference in which the intelligible speech from the undesired station is not noticeable. Of course, this interference is often classed as distorted speech but the distinction is convenient in the present discussion.

Case 2

In this case the programs are identical and consequently the speech from the two stations will undergo simultaneous fluctuations of intensity. We shall here assume that the two stations have the same degree of modulation at any instant. We may then take our data from the curves for which $M = m$. However this does not apply to the carrier beat note, since its intensity is independent of the degree of modulation of either station and its interfering effect will be determined by

[3] J. C. Steinberg, "The relation between the loudness of a sound and its physical stimulus," *Phys. Rev. Sec. Sc.*, **26**, pp. 507–523.

conditions which exist when the desired station has a low degree of modulation. Hence the discussion of this component of the interference will be exactly the same as in the preceding case.

Referring to Figs. 1 and 4, it is evident that by far the greatest portion of the displaced side band interference is due to the $q+u$ components, in the case of the straight line detector, and the $q \pm u$ and $p \pm u$ components in the case of the square law detector. The identity of the curves for these components in the two figures show that the degree of modulation has practically no effect on the relative importance of the interference which occurs when the same programs are transmitted.

If we again assume that the total interference may be represented by a fictitious componet of twice the amplitude of the $q+u$ component, we may take our data from the dash-dot line of Fig. 4. This should represent the case fairly well for the straight line detector but when a square law detector is used, greater interference should result due to the importance of the $p \pm u$ terms. However, we shall consider only the $q \pm u$ group and the phenomena associated with the square law case may be readily inferred. In order that the displaced side band interference may be 40 db down from the desired speech the carrier ratio must have a value of 0.01, while if it is to be 20 db down, this value must be 0.1. The first value corresponds to curves 5 of Figs. 5 and 6, while the second value corresponds to curves 8. We observe that there is a tremendous difference between the areas which may be considered to be free from displaced side band interference and those which will be free from carrier beat interference, in case the beat frequency is allowed to wander into the audible range. The comparison between the two areas is given by curves 1 and 5 for the 40 db interval and by curves 5 and 8 for the 20 db interval.

The speech from the interfering station will now be the same as the desired speech and can have effect only in so far as it adds to or subtracts from the desired speech. It will be noted from Figs. 1 and 5 that for carrier ratios of less than 0.1 this component is always down more than 40 db and may be safely neglected.

The foregoing discussion serves to illustrate the types of interference which may be expected when two stations are operated on approximately the same frequency. The data discussed have involved low values of attenuation. This is of particular interest when the distance between stations is large since with high values of attenuation either station will have very little effect on the service area of the other. Of course at nighttime we may have signal strengths which will be of the order of magnitude of that given by the simple inverse distance

law involving zero attenuation. This possibility probably presents a serious limitation on nighttime common frequency broadcasting but should be of little consequence during the daylight hours. Conditions will be somewhat different for stations that are placed nearer together and specific results can be readily computed for any given spacing. The equations which have been discussed can be applied to any such case and the areas corresponding to those in Figs. 5 and 6 determined.

One point which is emphasized by the results which have been obtained is, that with a carrier frequency difference of several cycles satisfactory reception cannot be expected in the regions which lie midway between two transmitters. The field strength of one station must be at all times predominately higher than that of the other and consequently the use of pseudocommon frequency broadcasting should be restricted to stations of wide geographic separation. It should then be possible to furnish high grade service to relatively small densely populated areas in the immediate vicinity of either transmitter, reception at a considerable distance from both stations being admittedly unsatisfactory. However if the carriers are strictly isochronous much larger service areas should be feasible.

Appendix

Equation (5) is

$$S=\overset{\mathrm{I}}{A+B}-\overset{\mathrm{II}}{\frac{AB(1-\cos ut)}{A+B}}-\overset{\mathrm{III}}{\frac{A^2B^2(1-\cos ut)^2}{2(A+B)^3}}-\overset{\mathrm{IV}}{\frac{A^3B^3(1-\cos ut)^3}{2(A+B)^5}}\cdots\cdots \tag{5}$$

To expand these terms we write

$$\begin{aligned}\frac{1}{(A+B)^n}&=\frac{1}{(E+e+ME\cos pt+me\cos qt)^n}\\&=\frac{1}{(E+e)^n}\Bigg(1-\frac{n(ME\cos pt+me\cos qt)}{E+e}\\&\quad+\frac{n(n+1)(ME\cos pt+me\cos qt)^2}{2(E+e)^2}\\&\quad\cdots+(-1)^r\frac{n(n+1)(n+2)\cdots(n+r-1)(ME\cos pt+me\cos qt)^r+}{r(E+e)^r}\Bigg)\end{aligned} \tag{5a}$$

It is evident there are present in S an infinite number of frequencies and it is necessary to select those which are of appreciable magnitude relative to that of the desired frequency of amplitude EM. Fortunately these are not very numerous.

In deciding whether or not a given term should be retained there

are two points to be considered: (1) whether all the terms of a given frequency total to a value sufficiently large to call for the presence of this term in the final result: (2) what per cent accuracy should be required in the frequencies which are retained. Thus if it is desired to retain all frequencies the relative amplitude of which is greater than 0.01 we cannot arbitrarily retain all individual terms which make a contribution of 0.01 or greater and neglect those of relative importance of less than 0.01. Thus if a term of a given frequency has a relative amplitude of 0.01 and another term of the same frequency a relative amplitude of 0.009 the second term should be retained. Otherwise we should have a large percentage error in the value of the amplitude of this frequency. On the other hand it is not desirable to maintain the same degree of accuracy for the case of retained frequencies of slight relative importance as for those of large importance. As a compromise all individual terms have been retained which, after division by EM, are of a magnitude greater than 0.005 for any values of M, m, and e/E which are here dealt with. An exception is made in the case of a term in cos pt derived from term III of (5). This term is slightly larger than the above limit when $M=0.5$ and $e/E=0.1$ but as it decreases rapidly with a decrease in e/E it has been omitted for the sake of simplicity.

Having chosen this limit of 0.005 for the relative magnitude of individual terms it can be shown to be permissible to neglect term IV and all subsequent terms of (5). Furthermore only a few of the large number of terms yielded by III need be retained.

After applying these rules there appear several frequencies that are never as large as 0.01 in relative magnitude and these have been omitted from consideration. As has been stated in the body of the paper, an exception is made in the case of the frequencies $(p \pm q \pm u)/2\pi$. If a given frequency exceeds 0.01 for any one of the four pairs of values of M and m, it has been shown on the figures for all of the pairs.

After the formula (5a) has been applied to S and the expressions for A and B inserted there remains the necessity of reducing products and powers of various sinusoidal terms to sums of simple first order sinusoids. This is a tedious procedure but is a matter of simple trigonometry and will not be set forth in detail.

From (5a) it can be seen that if M or m is near unity the series will converge very slowly. Furthermore, since to obtain relative magnitudes we divide by M it is impossible to obtain satisfactory convergence due to small values of M in the denominator. Hence it is necessary to limit M and m to 0.5 or less and in addition M must be no smaller than 0.1. It would be permissible to allow m to become less than 0.1 but as little would be gained by this m has been restricted to the same range as M.

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SIMULTANEOUS ATMOSPHERIC AND CABLE DISTURBANCES*

By

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(Communication from the Reichspostzentralamt, Telegraphentechnisches Reichsamt, Berlin-Tempelhof, Germany)

Summary—*A description is given of tests made to determine whether there is a relation between the interference currents in submarine cables and the atmospheric interference in radio. Racorder and oscillograph photographs show the agreement in a large number of interference signals. Cable and antenna, therefore, are influenced similarly by the same interference processes.*

Atmospheric disturbances in wireless telegraphy are assumed to be due to sudden changes in the condition of the electric field in the air, or in the magnetic field of the earth. The sudden changes accompanied by lightning in storms, not only influence radio antennas but also overhead telephone lines. Lightning near telephone lines is identified easily by sharp crackling in the receiver. In submarine cables, particularly in the summer, there are

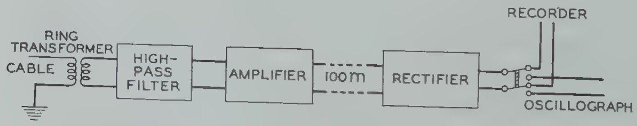

Fig. 1.

interference currents also due to natural electric and magnetic transients. In August, 1929, at Borkum, during interference measurements on a section of the new single-core cable from Emden to Vigo, tests to explain this question were made by determining the simultaneity of atmospheric and cable interferences and the results will be given in the following. The tests were made by Dr. Haak and O. Fuchs.

In the investigation, the interference currents from the cable and the atmospheric interference in an antenna, were recorded with a double-recorder or two-string oscillograph. The following apparatus and connections were used:

The submarine cable was closed by a transformer whose primary winding was connected between the cable core and cable sheathing (Fig. 1). A quadruple tube amplifier (Siemens and Halske type) operating in the voice-frequency range, was connected to the ring trans-

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former through a high-pass filter. The high-pass filter was for the purpose of excluding from the amplifier any telegraph signals from adjacent submarine cables. The interference currents from the amplifier were carried by a 100-meter twisted underground double line, through a rectifier in the plate rectifier connection, to the recorder or oscillograph.

For radio reception from 30 to 100 meters, *L*-shaped antenna wires were used. The receiver (Fig. 2) was an arrangement consisting of an

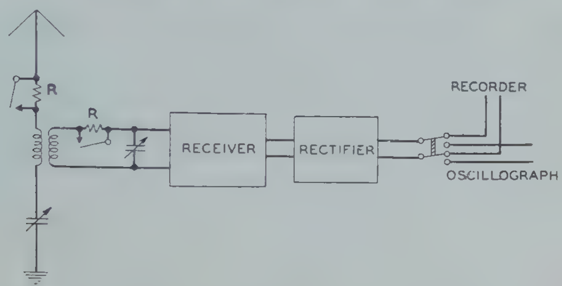

Fig. 2.

oscillating detector with a triple low-frequency resistance amplifier to which the recorders could be connected through a rectifier of the type mentioned above. The two receiving sets were so far apart that no effect of one on the other could be detected. In addition, interference signals could not be detected by telephone, recorder, or oscillograph when the cable or antenna was disconnected. The records were made with these two recording instruments so that an observation was possible over a longer period of time and a finer subdivision of the interfering impulses could be determined.

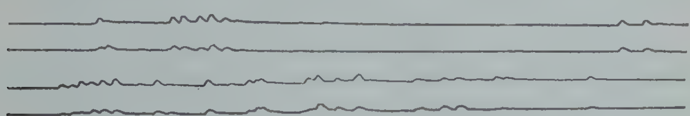

Fig. 3.

The wireless receiving set was tuned to frequencies of 25, 242.9, 600, and 8823.5 kilocycles (12000-1400-, 50-, and 34-meter wavelengths) and damping resistances of 300–5000 ohms were connected in the antenna and intermediate circuit. The receiving set for the cable was not changed. A damping resistance was inserted in order to adapt the antenna to the cable as far as possible.

Figs. 3 to 7 reproduce some record photographs taken with a tape speed of 60 cm per min. The upper line is for the cable and the lower

for the antenna. The concordant interference impulses can be recognized plainly. Figs. 8 to 13 show oscillograms. The thick black line (the zero line) corresponds to the general interference level from which project the heavier current impulses as sharp peaks Because of its

Fig. 4.

greater sensitivity the oscillograph has detected many more interferences than the recorder which has indicated only the strongest impulses and combined several short interference surges because of its inertia. Among the numerous interference signals on the oscillograms we find

Fig. 5.

a large number of corresponding interference impulses from the cable and antenna. The agreement is striking in cases in which the amplitudes of the interference process in the antenna extend into those of the cable in the diagram. On closer observation we see that the ampli-

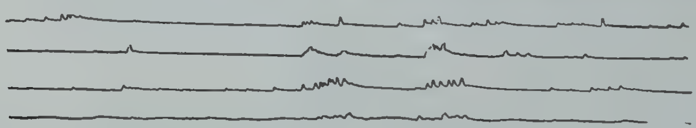

Fig. 6.

tude ratio of the single interference impulse varies. The related interference signals are sometimes stronger in the antenna and sometimes stronger in the cable. Attention is called to the differences in the two photographs (not perfect agreement of all interference signals and

Fig. 7.

varying amplitude) in order to overcome the objection that the two receiving sets might have influenced each other. Fig. 13 also belongs here. The alternating-current impulses induced in the cable from an adjacent cable, cannot be seen on the antenna tape. In regard to the number of interferences, a difference in the photographs by the un-

damped and strongly damped wireless receiving set could not be detected.

In August, 1927, when measurements were made on the permalloy cable from Emden to the Azores, Dr. H. Salinger drew the interference currents of this cable and an older Emden-Vigo cable simultaneously

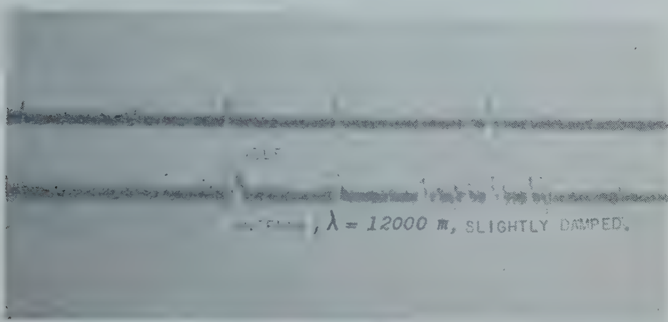

Fig. 8.

with recorder and oscillograph. Fig. 14 shows a record strip. The two marking capillaries of the recorder were 2.5 mm apart in the direction of the tape motion, and in addition the recorders have opposite polarity. The lower line is for the permalloy cable, and the upper is for the old Vigo cable. Simultaneous points are indicated by arrows. The deflec-

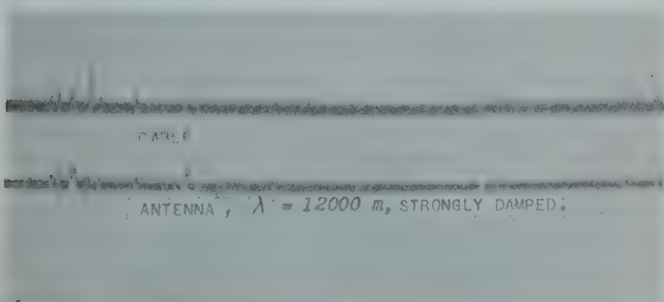

Fig. 9.

tions indicate very great interferences, 20 of which were counted in 22 minutes. A picture of such an interference impulse taken with oscillographs is shown in Fig. 15, in which the upper is the Vigo cable and the lower is the permalloy cable. The vertical lines are at intervals of 0.01 second. Both cables were connected to nondistorting amplifiers. The interference surges were so strong that the amplifier for the Vigo cable frequently was completely blocked, and the other was blocked occa-

sionally. The two curves are shifted apart somewhat. This depends on the different rate of propagation of electric waves or currents in the

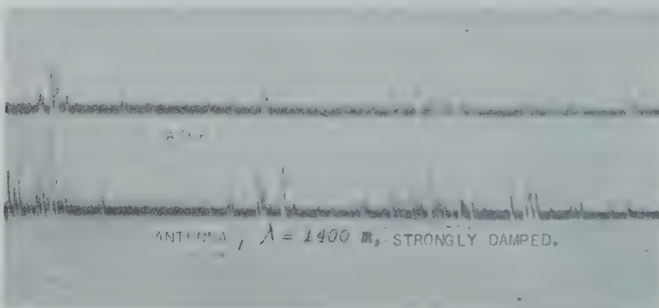

Fig. 10.

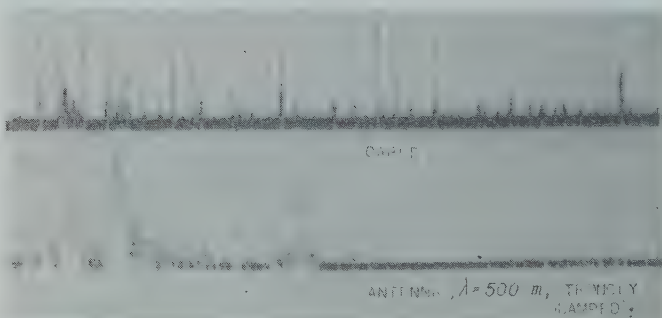

Fig. 11.

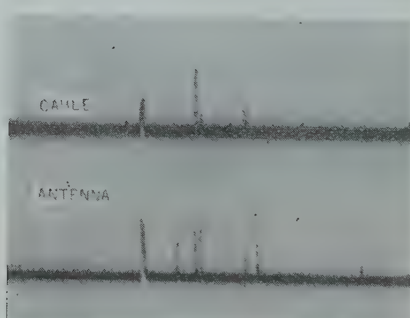

Fig. 12.

two cables. In the permalloy cable it is about 10,000 km per sec. On the average the Vigo cable is superior to the other one by 0.022 sec. If the propagation velocity in the Vigo cable is assumed to be very high

in relation to that in the other cable, the difference in time would correspond to a distance of not more than 200 km from Borkum at which the interference processes could penetrate the cable. It was found later

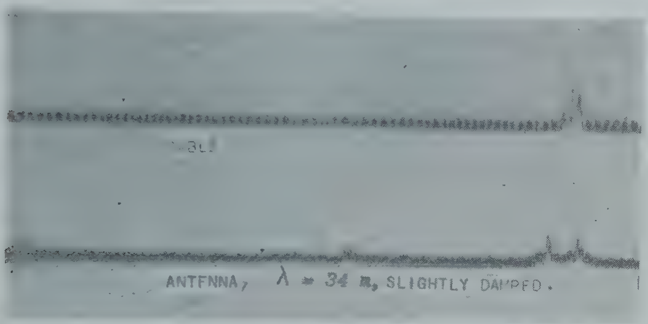

Fig. 13.

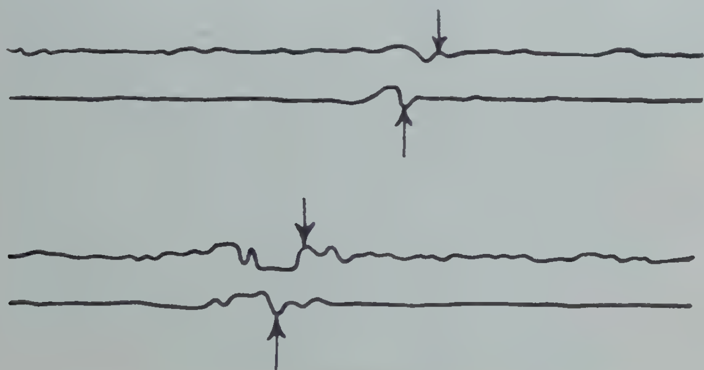

Fig. 14.

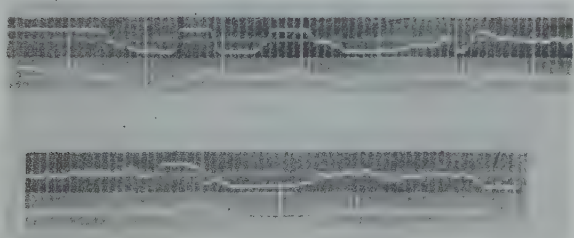

Fig. 15.

that there was a severe thunderstorm on the Holland coast during the tests. Because of this, it is possible that the interference impulses were caused by lightning. The two cables run from Borkum to the Channel

at the bottom of the sea on about the same path so that the identical influences by the same interference process can be explained.

From the agreement in the time of a number of interferences, it can be concluded that the interference impulses had to come from the same source of disturbance. It also is probable that the interference impulses in the cable, which were not opposite simultaneous interference signals in the antenna, should be ascribed to the same interferences as in radio. The investigation also showed that the interferences did not start in the immediate vicinity of the testing station but came from rather great distances. Since the cable cores cannot be influenced by electric fields the interference currents can be due only to magnetic induction.

Proceedings of the Institute of Radio Engineers
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DISCUSSION ON WHISTLING TONES FROM THE EARTH*

A. M. Curtis†

The Bell Telephone Laboratories sent an expedition last summer to Newfoundland for the purpose of measuring the interference picked up on an 8-mile submarine cable in order to determine the amount of interference which might be expected on a transatlantic telephone cable terminated there. The same expedition is engaged in similar measurements this year in Ireland.

The "swishes" discussed by Dr. Barkhausen were noted in both locations both day and night and were received on a loop of wire as well as on several different types of submarine cables. They are of two types, one descending in pitch, as mentioned by Dr. Barkhausen, and the other type ascending in pitch. The range of frequencies covered by the swishes was found to lie usually between 700 and 2000 p.p.s. The individual swishes, however, did not often exceed an octave in range.

Another type of musical interference not as yet described by other observers, and called "tweeks" by our engineers because of their characteristic sound, occur only at night. They appear to the ear to be highly damped oscillations the frequencies of which are generally in the range between 1600 and 2200 p.p.s. We have tried to explain these tweeks as the result of multiple reflections between the earth and the Heaviside layer of a single static discharge and believed that this explanation was substantiated by the fact that they were never noticed during the daylight hours when the Heaviside layer is believed to be a less efficient reflector than during the dark hours. This conflicts somewhat with Dr. Barkhausen's explanation of the formation of the swishes since they appear to have the same general characteristic when noted at any time during the day or night. It might be expected that any phenomenon depending on reflection from the Heaviside layer would show characteristics during the night differing noticeably from those observed during the day.

A more complete description of these phenomena as noted in Newfoundland is given in E. T. Burton's letter published in Nature, July 12, 1930.

* H. Barkhausen, Proc. I. R. E., 18, 1155; July, 1930.
† Bell Telephone Laboratories, New York City.

BOOK REVIEWS

The National Physical Laboratory Report for the Year 1929. Published by His Majesty's Stationery Office, London. 298 pp. $8 \times 10\frac{1}{2}$. Paper binding. Price 11 s. net.

This is a complete report of the research work and testing carried on by the National Physical Laboratory during 1929. It consists of a report of the executive committee and a report on each of the following departments: Physics, Electricity, Metrology, Engineering, Aerodynamics, and Metallurgy. The progress made on each problem has been briefly outlined and a list of publications given.

The radio work, which represents a small fraction of the total work, is outlined in the report on the Electricity Department. This indicates the progress which has been made in basic frequency measurements, behavior of quartz oscillators, studies of radio antennas, antennas for beam transmission, ultrashort waves from 20 megacycles up, directional radio, receiving apparatus, receivers for ultrashort waves, measurement of current, resistance and reactance at radio frequencies, and measurement of power factor of variable condensers.

An account is also given of work on sound transmission, measurement of sound absorption coefficients and sound intensity.

S. S. Kirby*

* Bureau of Standards, Washington, D.C. 148.

Photocells and their Application. by V. K. Zworykin and E. D. Wilson. John Wiley and Sons, New York. 209 pp. $5\frac{1}{2} \times 8\frac{1}{2}$. Price $2.50.

The photocell, invented before the thermionic tube, for a long time remained rather obscurely in the background. With the discovery that feeble photoelectric currents could be efficiently amplified by means of the thermionic tube the photocell has come into its own. The general reader is not yet entirely familiar with this device. This book provides an understandable account, not too technical for the untrained man and not too shallow for the specialist, of the origin and rise of the photocell and its behavior and functioning.

The book opens with an interesting historical account of the work of Hertz, Hallwachs, Elster, and Geitel. This is followed by a discussion of radiant energy, photo-emissive effect and Einstein's photo-electric equation. The mechanical features such as arrangement of parts, shapes, and sizes of photocells, and general methods of preparing cells, are clearly explained. The vacuum photocell is described and compared with the gas-filled cell. A discussion of photocell circuits leads to the problem of amplification which is treated at considerable length. The applications of photocells in sound movies, facsimile transmission, and television are outlined clearly. The book closes with a chapter on the future of photocells indicating the trend of advance and improvement.

S. S. Kirby*

* Bureau of Standards, Washington D.C. 149.

BOOKLETS, CATALOGS, AND PAMPHLETS RECEIVED

Copies of the publications listed on this page may be obtained gratis by addressing a request to the manufacturer or publisher.

"Technical Bulletins on RCA Radiotrons" is the title of a loose leaf booklet of operating data and circuits for Radiotron receiving tubes. In the case of triodes and tetrodes, a family of plate characteristics is given in addition to the data already mentioned. The data sheets initially supplied are those dealing with the following tubes: UX-281, UX-280, UX-245, UY-227, UX-226, UY-224, UX-222, and UX-171-A. The folder is issued by the Commercial Engineering Department, RCA Radiotron Co., Harrison, N. J.

Bulletin D, of the Aircraft Radio Corporation, Boonton, N. J. describes the Model D aircraft receiver designed by the Aircraft Radio Corporation and manufactured by the Stromberg-Carlson Telephone Manufacturing Company. The receiver is designed for the reception of radio beacon signals, weather reports, and other aids to the operation and safety of aircraft. By means of six sets of interchangeable coils, a frequency range of from 235 kc to 8000 kc is covered. A 10 microvolt signal will produce a signal output of 10 milliwatts. One 227 tube and four 224 tubes are employed. A 12-volt storage battery supplies the power for the receiver.

A 12-page booklet is available from the National Company of Maiden, Mass. describing the National M.B. 30 broadcast tuner.

A 4-page folder from the Littlefuse Laboratories, 1772 Wilson Ave., Chicago, lists low current fuses for the protection of meters, vacuum tubes, rectifiers, etc. Several fuses for use in high voltage circuits are listed.

The eighth edition of the general catalog of the Weston Electrical Instrument Corporation, of Newark, N. J. contains a number of comparatively new items of interest to radio engineers in addition to the familiar and standard line of switchboard and portable instruments. Among these are the model 301 rectifier type a-c instruments which are identical in appearance with the popular model 301 d-c instruments, the model 489 d-c volt-milliammeter for automobile radio receivers, the model 506 voltohmmeter, the model 540 portable d-c voltammeter, the model 563 d-c circuit tester, the model 564 voltohmmeter, and the model 565 radio set tester and tube checker.

REFERENCES TO CURRENT RADIO LITERATURE

THIS is a monthly list of references prepared by the Bureau of Standards, and is intended to cover the more important papers of interest to the professional radio engineer which have recently appeared in periodicals, books, etc. The number at the left of each reference classifies the reference by subject, in accordance with the "Classification of Radio Subjects; an Extension of the Dewey Decimal System," a revised edition of Bureau of Standards Circular No. 138 which appeared in full on pp. 1433–56 of the August, 1930, issue of the Proceedings of the Institute of Radio Engineers. The classification numbers are in some instances different from those used in the earlier version of this system (first edition of Circular 138) used in the issues of the Proceedings of the Institute of Radio Engineers before the October, 1930, issue.

The articles listed are not obtainable from the Government or the Institute of Radio Engineers, except when publications thereof. The various periodicals can be secured from their publishers and can be consulted at large public libraries.

R100. Radio Principles

R113 Wise, W. H. Note on the accuracy of Rolf's graphs of Sommerfeld's attenuation formula. Proc. I.R.E., **18**, 1971–72; November, 1930.

Discussing an approximation not mentioned by Rolf, which imposes a considerable restriction on the range of applicability of his graphs where high frequencies and poor conducting grounds are concerned.

R113.2 Prescott, M. L. The diurnal and seasonal performance of high-frequency radio transmission over various long distance circuits. Proc. I.R.E., **18**, 1797–1920; November, 1930.

This paper presents a quantity of radio wave propagation data that has been obtained during the past six years by the General Electric Co. through the use of its development transmission facilities at South Schenectady, N. Y. Nineteen radio circuits which radiate in various directions from Schenectady are treated. These circuits range in length from 2300 to 11,400 miles. Data are given which will aid in determining the proper frequency to use in any high-frequency radio circuit from 1000 to 10,000 miles in length. It is shown that the daylight-darkness distribution over the path of propagation largely determines the diurnal and seasonal performance of high-frequency transmissions.

R113.61 Gilliland, T. R. Kennelly-Heaviside layer height observations for 4045 and 8650 kc. *Bureau of Standards Jour. of Research*, **5**, 1057–61; November, 1930. Research Paper No. 246.

Virtual heights of the Kennelly-Heaviside layer as measured by the radio-echo method are reported for 4045 and 8650 kc. The report covers daytime observations made each week between January 16 and June 19, 1930. Two evening tests are also described. Curves are given comparing heights with sun spot numbers and magnetic character. Records taken on April 28, 1930, the day of the solar eclipse, are shown.

R116 Roosenstein, H. O. Die Fortleitung hochfrequenter elektrischer Schwingungsenergie. (The transmission of high-frequency electrical wave energy). *Zeits. für Hochfrequenz.*, **36**, 81–85; September, 121–33, October, 1930.

The characteristics of a Lecher wire transmission line are investigated both from a theoretical and experimental point of view. The transmission efficiency and its dependence on the output impedance is determined. Methods for determining the impedance, attenuation factor, and for producing necessary symmetry in such a system are given.

R120 Kiebitz, F. Neuere Versuche mit Sendeantennen. (Recent experiments with transmitting antennas). *Telegraphen und Fernsprech Technik*, **19**, 303–308; October, 1930.

The results of field strength measurements made on a transmitter operating at $\lambda = 400$ meters and exciting a vertical antenna, one end of which could be raised to a height of 200 meters, show that the signal strength increases as the height of transmitting antennas is increased with $1/4\lambda$ as the limit. A further increase in antenna height has no effect on signal strength.

R129 Peters, H. Messungen im Strahlungsfelde einer in der Grundschwingung ungedämpft erregten Dipolantenne. (Measurements on the radiation characteristic of a dipole antenna excited at its fundamental frequency with undamped oscillations). *Elek. Nach. Tech.*, **7**, pp. 378–86; October, 1930.

The author describes a four-tube, push-pull oscillator, working at $\lambda = 7.15$ meters which is coupled by means of a Lecher transmission line to a dipole antenna located 26 meters above the earth. Two types of receiving sets are described; one with and the other without regeneration. Using the apparatus described, radiation characteristics of the dipole antenna were obtained. The results were shown to substantiate Abraham's theoretical work for distances up to 4000 meters. The results also show, a rotation of the plane of polarization and a tendency toward elliptic polarization, both of which increase as distance wavelength increases.

R133 Page, R. M. and Curtis, W. F. The van der Pol four-electrode tube relaxation oscillation circuit. Proc. I.R.E., **18**, 1921–29; November, 1930.

Relaxation oscillations of an electrical nature are defined, and the operation of a tetrode relaxation circuit is described in detail. The mechanism of frequency division is explained, and oscillograms of the oscillations in this circuit are shown, both of the free oscillation and of the oscillation as controlled in frequency division. The characteristics of the oscillator are discussed with reference to frequency drift and stability of frequency division. The period of the oscillator is shown to be approximately $RC \log V_1/V_2$ where V_1 and V_2 are initial and final voltages on the condenser, respectively, during the discharge. V_1/V_2 is shown to change very steeply with average internal grid resistance. Modifications are shown for increasing frequency stability and over-all efficiency of the system, and for controlling the ratio of charging time to discharging time of the condenser. A further modification is suggested for making the internal grid resistance independent of filament voltage when the grid is positive.

R133 Gerber, W. Raumladungsschwingungen in Dioden. (Space charge oscillations in diodes.) *Zeits. für Hochfrequenz.*, **36**, 98–112; September, 1930.

It is shown that oscillations occurring in diodes, where both electrodes are thin filaments (only one of which is heated), correspond to Barkhausen-Kurz oscillations. The conclusion contradicts the popular conception that these latter are restricted to tubes with concentric electrodes.

R133 Wundt, R. Über freie Schwingungen einer Elektronenröhre mit Lecher-System. Barkhausen-Kurz Schaltung. (Free oscillations with a vacuum tube and Lecher system using the Barkhausen-Kurz circuit). *Zeits. für Hochfrequenz.*, **36**, 133–146; October, 1930.

The oscillating characteristics of a specially built flat-electrode vacuum tube using the Barkhausen-Kurz circuit, were experimentally investigated. It is shown that oscillations may be produced with such a tube, even though several investigators have failed in this respect. It is pointed out that symmetry of the electrodes is essential. The theoretical and experimental results are discussed, compared, and shown to harmonize with those obtained by Hollmann with tubes having cylindrical electrodes.

R139 Groszkowski, J. Frequency division. Proc. I.R.E., **18**, 1960–70; November, 1930.

It is demonstrated that the division of frequencies, that is, the inverse process from frequency multiplication, is possible by using a triode arrangement. The requirements of such a circuit are analyzed theoretically and the conditions resulting from this study are tested experimentally. Curves are included showing the results of these experiments when the initial frequency bears a ratio to the final frequency equal to a small integral number.

R148 Smith, C. H. Note on the relationships existing between radio waves modulated in frequency and in amplitude. *Exp. Wireless & W. Engr.*, **7**, 609–611; November, 1930.

An analysis of the general principles governing the composition of a frequency modulated wave and the relation in which it stands with regard to amplitude modulation leads to several important conclusions.

R148 Rieche, H. Die idealisierte statische Modulationskennlinie bei der Parallelröhren-Modulation. (The ideal static modulation characteristic for parallel-tube modulation). *Zeits. für Hochfrequenz.*, **36**, 112–113; September, 1930.

Working from Barkhausen's elementary equations, an equation is developed for the parallel-tube modulation circuit. Experimental results are compared with and found to verify results computed from this equation. Further conclusions lead to the determination of optimum dimensions for modulation and transmitting tubes.

R148 Weichart, F. and Langewiesche, W. Eine vereinfache Modulationsschaltung. (A simplified modulation circuit). *Elek. Nach. Tech.*, **7**, 408–409; October, 1930.

It is possible to eliminate certain inherent disadvantages in ordinary methods of furnishing filament supply for the modulating tube, when grid-modulation is employed. This is done by heating the filament of the modulating tube with a high-frequency current which is absorbed from the oscillator.

R149 Colebrook, F. M. The theory of the straight line rectifier. *Exp. Wireless & W. Engr.*, **7**, 595–603; November, 1930.

Analysis of the theory of operation of a straight line rectifier, i.e., a rectifier which shows very high (effectively infinite) resistance to currents in one direction and constant resistance to currents in the opposite direction.

R200. Measurements and Standardization

R210 Decaux, B. Le fréquencemetrè étalon absolu du Laboratoire National de Radioélectricité. (The primary frequency standard of the National Laboratory of Radioelectricite). *L'Onde Electrique*, **9**, 449–66; October, 1930.

A detailed description of the frequency standard equipment of the National Laboratory of Radioelectricite including the description of an electron-tube maintained tuning fork which is accurate to 1 part of 10^5.

R214 Jimbo, S. An international comparison of frequency by means of a luminous quartz resonator. Proc. I.R.E., **18**, 1930–34; November, 1930.

The international comparison of frequency standards made with the luminous quartz resonator shows the different laboratories,—Physikalischtechnische Reichsanstalt, National Physical Laboratory, Bureau of Standards, and Electrotechnical Laboratory,—to be in agreement to one part in 10^5 when used to calibrate the resonator at its flexural fundamental of about 10 kc, due allowance being made for the temperature coefficient of the resonator in this mode, namely, about 1 part in 10^5 and negative. The observed agreement seems limited by the luminous glow resonator used rather than by any difference between the laboratory standards compared.

R214 Koga, I. Characteristics of piezo-electric quartz oscillators. Proc. I.R.E., **18**, 1935–59; November, 1930.

Piezo-electric quartz oscillators are very satisfactory in their stability of frequency but their frequencies are obviously somewhat influenced by several factors associated with the circuits. Starting with the Barkhausen equation, their behavior is analyzed.

R243.1 Metcalf, G. F. and Thompson, B. J. A low grid-current vacuum tube. *Phys. Rev.*, **36**, 1489–94; November 1, 1930.

The various factors that may cause a current to flow to the control grid of a high-vacuum tube are outlined. The magnitudes of the separate components are experi-

mentally determined, and methods are given by which these currents may be greatly reduced. A tube is described which has a grid current of 10^{-15} ampere and mutual conductance of 25 microamperes per volt. As an input resistance of 4×10^{11} ohms may be used, a current of 10^{-17} ampere may be detected when a galvanometer having a sensitivity of 10^{-10} ampere per millimeter is used in the plate circuit. Under this condition the sensitivity 250,000 millimeters per volt.

R280 The thermal resistivity of solid dielectrics. *Jour. I.E.E.* (London), **68,** 1313–55; October, 1930.

A report on the results of an experimental investigation on the thermal resistivity of dielectrics, carried out as part of a comprehensive program of Researches on Dielectrics, by the British Electrical and Allied Industries Research Association.

R280 Strutt, M. J. O. Messungen der elektrischen Erdbodeneigenschaften zwischen 20 und 2×10^7 Hertz. (The measurement of the electrical constants of soil between 20 and 2×10^7 cycles). *Elek. Nach. Tech.*, **7,** 387–93; October, 1930.

Measurements made on moderately damp meadow soil led to the following results: (1) Between 20 and 500 cycles the conductivity increases about 30 per cent. Between 500 and 2×10^7 cycles it remains practically constant at a value of 5×10^{-14} e.m.u. (2) The measured dielectric constant before a rain was 10, after the rain it was 15. These values were nearly constant for the frequencies varying from 10^5 to 2×10^7 cycles.

R282.2 Pätzold, J. Die Erwärmung der Elektrolyte im hochfrequenten Kondensatorfeld und ihre Bedeutung für die Medizin. (The temperature rise of electrolytes exposed to a high-frequency capacitive field and its import to the field of medicine). *Zeits. für Hochfrequenz.*, **36,** 85–98; September, 1930.

The results of a mathematical investigation of the effects of high-frequency condenser fields on various substances were verified by experiment. Further, the wavelength for which the maximum energy is absorbed by the liquid was determined for blood, bullion, serum and agar-agar.

R300. Radio Apparatus and Equipment

R339 von Ardenne, M. Über Verstärkerröhren mit photoelektrischer Emission. (On amplifying tubes with photo-electric emission). *Zeits. für Hochfrequenz.*, **36,** 146–151; October, 1930.

Using a three-electrode, gas-filled tube which depends on the photo-electric effect for electron emission from the cathode, the author has obtained, at low frequencies, a voltage amplification of 10–30 per stage. The author discusses the problems connected with the further development of this type of tube, especially the problem of obtaining a constant emission from the cathode.

R355.4 Chinn, H. A. and Hendricks, P. S. A modern 50-watt radiophone transmitter. *QST*, **14,** 19–25, November, 1930.

A detailed description of the design and construction of an efficient transmitter, having a frequency range of 3,000–17,000 kc, a carrier output of 50 watts, a good over-all audio-frequency characteristic and capable of high percentage modulation. The radio frequency circuit consists of a type '10 oscillator, a '65 buffer and amplifier and a '11 output amplifier. The oscillator is arranged to operate with crystal control if crystal is available. The audio-frequency circuit has three stages of speech amplification using two '12A's and a '50 with two 845s in push-pull for modulating the '11.

R361 Gill, A. J. and McDonald, A. G. Developments in broadcast radio receiving apparatus. *Post Office Elec. Engrs. Jour.* **23,** 216–19; October, 1930.

A brief discussion of the more recent developments in broadcast receivers and their components.

R400. Radio Communications Systems

R423.4 Deloraine, E. M. La liaison radiotéléphonique Madrid-Buenos Aires. (The Madrid-Buenos Aires radiotelephone circuit). *L'Onde Electrique*, **9,** 467–83; October, 1930.

A description of transmitting, receiving and directive antenna equipment used in the recently completed Madrid-Buenos Aires radiotelephone circuit, which operates on frequencies between 5000 and 20,000 kc. and provides a linkage between the telephone networks of Europe and South America.

R423.5 Whitehead, C. C. Practical experiments in ultrashort wave communication. *Exp. Wireless & W. Engr.*, **7**, 542–51, October; 612–620, November, 1930.

A series of range tests and experiments upon propagation using wavelengths of the order of 3 meters, show that these ultrashort waves may be used efficiently under conditions similar to those required for light wave communication. The description of a simple, stable, and practical outfit for the generation and reception of these waves is given.

R423.5 Beauvais, G. Résultats experimentaux de télécommunications avec les ondes ultra-courtes. (Results of experiments with ultrashort waves). *L'Onde Electrique*, **9**, 484–92; October, 1930.

Using parabolic reflectors and wavelengths of the order of 15 to 18 cm, communication was established over a distance of 23 km. Reception was possible up to a distance of 9 km through a fog where the visibility was less than 100 meters. A description is given of the circuits and apparatus employed in these experiments, as well as of methods used in selecting suitable vacuum tubes for working at these high frequencies.

R500. Applications of Radio

R520 Völkel, W. Die Elektrische Ausrüstung des Dornier-Flugschiffes Do-X. (The electrical equipment of the Dornier airplane Do-X). *Elek. Zeit.*, **51**, 1541-42; November 6, 1930.

A description of the electrical equipment carried by the world's largest airplane is given, including a brief description of its radio installation.

R526 Sibley, E. Aeronautical radio communications. *Jour. A.I.E.E.*, **49**, 918–20; November, 1930.

A brief survey of communication facilities which are being provided along the U. S. Airways by the Federal Government. These facilities consist of a network of land line services, airways radio stations, and oradi range stations along the airways, for collecting and broadcasting weather information and for the guidance of aircraft by radio direction. A system of marker beacons serve to mark the intersection of the radio range courses and to give the pilot his exact position along the route. The present facilities are to be extended to include two-way communications between the airport and transport aircraft.

R526.3 Diamond, H. and Dunmore, F. W. A radiobeacon and receiving system for blind landing of aircraft. *Bureau of Standards Jour of Research*, **5**, 897–931; October, 1930. Research Paper No. 238.

A radiobeacon and receiving system is described for use at airports to permit the blind landing of aircraft under conditions of no visibility. The system comprises three elements (horizontal, lateral, and vertical guidance), indicating to the pilot the positon of the aircraft as it approaches and reaches the instant of landing. A unique feature is the ultra high-frequency radio beam, used in such a way as to provide a safe, and convenient gliding path for the landing airplane. The receiving equipment on the airplane consists of a light and compact ultra high-frequency receiving set in addition to the usual medium frequency receiving set.

R600. Radio Stations

R617 Farnes, G. H. and Hollinghurst, F. Radio direction finding at Post Office Coast Stations. *Post Office Elec. Engrs. Jour.*, **23**, 211–15; October, 1930.

The equipment used for direction finding at British Post Office Coast Radio Stations is described. A Bellini-Tosi cross-coil antenna is coupled through a goniometer to the receiving set which uses six stages of aperiodic r.f. and two stages of l.f. amplification. By means of a three-point switch the cross-coil antenna may be coupled to the receiving set in three ways. The first position of the switch connects the antenna to act as a simple vertical aerial with circular characteristic, in the second position of the switch, the antenna has a "figure-of-eight" characteristic and in the third position, the directional characteristic of the antenna is a cardioid. The goniometer scale is calibrated in degrees from North and it requires about 1½ minutes to take a bearing on a distant station.

R800. Nonradio Subjects

621.375.1 Laub, H. Die Glimmlampe als Relais. (The glow discharge tube as a relay). *Elek. Nach. Tech.* **7**, 374–77; October, 1930.

An analysis of the current-voltage characteristic of a glow-discharge tube reveals its peculiar adaptability to operate as a relay. The effect of series and parallel resistance on the action of such a tube relay is explained and the results of an oscillographic investigation of several types of glow-discharge tubes is given.

621.375.1 Ruedy, R. The use of discharge tubes in electric circuits. *Jour. Franklin Institute*, **210**, 625–44; November, 1930.

After considering the valuable properties of an electric discharge through a gas at low pressure, the author discusses applications of such a discharge in the problems of automatic controlling circuits. He further describes the action and necessary characteristics of such a discharge tube when operating as a voltage reducer, voltage regulator, rectifier, relay, photo-electric cell, or as a source of light.

CONTRIBUTORS TO THIS ISSUE

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